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TWO-PHASE CONVECTION IN IGNEOUS MAGMAS[1]

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A careful study of the Duluth gabbro led the writer to the idea of a convection circulation in the magma. A review of the literature shows nothing conclusively opposed to the idea, though the structures are explained in many other ways. This paper summarizes the signs of convection and suggests its probable mechanism and results.

SIGNS OF CONVECTION IN MAGMAS

1. The fluxion structure of many rocks is a strong indication that movement occurred during crystallization. When combined with an alternation of differentiated bands and a roughly gravitative arrangement of the bands, the only explanation that is at all satisfactory is that the movement is one of circulation rather than of intrusion or of deformation.[2]

2. Convection has been observed directly in lava lakes in the craters of volcanoes. These highly special conditions of magma, however, are not sufficient to convince everyone that convection is a common process in deeper magmas.

[1] Part of a thesis presented to the faculty of Yale University for the degree of Doctor of Philosophy.

[2] Frank F. Grout, "Internal Structures of Igneous Rocks," etc., *Jour. Geol.*, XXVI, No. 5 (1918).

3. The texture of an intrusive mass in relation to its borders and its contact metamorphism may be a sign of convection. Lane[1] and Queneau[2] have shown that in the case of simple conduction of heat away from a stationary mass the grain of the rock will not be uniform up to the contact unless the magma temperature was farther above the temperature of crystallization than the wall-rock temperature was below. As Lane puts it, measured from the temperature of the surrounding rock as zero, the magma must be more than twice the temperature of solidification. For an intrusion at moderate depths into cold rocks, this means more superheat than is commonly supposed to exist. The observed superheat is seldom over 200° to 300°C.

4. The arrangement of the extreme differentiates in a laccolith might be a strong indication of convection. If the outer layer is of average composition it may be attributed to chilling, but if a layer found on all sides, top and bottom, is an extreme of the series of differentiates it can be attributed to neither chilling nor gravity. An illustration is found in the Lugar sill in Scotland.[3] The average material of the sill has scarcely 20 per cent of salic constituents, but the border phases have over 40 per cent of feldspar and feldspathoid material. Since diffusion is shown to be too slow a process,[4] the only way to get the extreme product segregated to all sides is by a circulation of some sort.

5. A differentiated dike found by the writer at Duluth is very suggestive. The dike is four feet wide and is pegmatitic in nature a few feet below the base of the main gabbro. Its texture is particularly coarse at the sides, where the composition is that of a gabbro, and it is evident that the crystals must have grown large by additions from the residual circulating or passing magma in the center of the dike. From these coarse gabbro borders there is a complete gradation to a medium-grained red granite in the center of the dike.

[1] A. C. Lane, "The Grain of Rocks," *Bull. Geol. Soc. Am.*, VIII, 403.

[2] A. L. Queneau, *School of Mines Quarterly*, XXIII (1902), 181.

[3] G. W. Tyrrell, "Alkaline Igneous Rocks of West Scotland," *Geol. Mag.*, IX (1912), 75–77.

[4] N. L. Bowen, "Later Stages of Evolution of Igneous Rocks," *Jour. Geol.*, Supplement, December, 1915, p. 12.

There is no sign whatever of an internal contact between the two rocks such as would indicate successive intrusions. Neither is there any fluxion structure such as a strong extrusive movement during crystallization would be expected to produce. It is much more likely that the gabbro and granite separated from the same liquid, and that this was moved about only slightly, by convection or by a late phase of injection, so that the supply of basic minerals to the sides was continuous until all had crystallized.

THE MECHANICS OF CONVECTION IN IGNEOUS MAGMAS

The nature of convection.—The familiar illustration of convection is the local heating of a tank of water, with some suspended matter to make its motion visible. The density in different parts of the tank is different enough to start a motion of readjustment, and if the difference is maintained by a continuous heat supply and continuous cooling elsewhere, a circulation is maintained. As applied to magmas the process was suggested by Becker and has been widely applied.[1] The chief factors which control the rate of circulation are the differences in density in different parts of the container and the viscosity of the liquid; and both of these factors vary with temperature. Water, which is the liquid in most laboratory experiments, shows a very great density change with temperature, and its viscosity is very low as compared with that of igneous magma. Both conditions being exceptionally favorable, it is clear that the illustration should not be applied to magmas without some estimate of its quantitative importance.

Two-phase convection.—Besides the well-known changes in density in a magma from changes of temperature, there are other density effects due to a separation of phases. The separation of gases and crystals from lava is a matter of common observation. The separation of gases was suggested by Pirsson[2] as a possible means of deep-seated stirring, and the idea was further developed by

[1] G. F. Becker, "Some Queries on Rock Differentiation," *Am. Jour. Science*, III (1897), 21. L. V. Pirsson, "The Igneous Rocks of the Highwood Mountains," *U. S. Geol. Surv. Bull. 237*, pp. 184 and 189.

[2] L. V. Pirsson, "The Petrographic Province of Central Montana," *Am. Jour. Sci.*, XX (1905), 47.

Daly[1] in explaining the supply of heat from depth to lava lakes—he called it two-phase convection.

It seems perfectly clear, from a general consideration of the idea, that a mass of lava filled with bubbles would have a lower "aggregate specific gravity" than a neighboring mass without such bubbles. Any process of local vesiculation would almost certainly result in convection. It is perhaps less clear and less often emphasized, but none the less true, that a mass of lava in which crystals have formed has a greater "aggregate specific gravity" than it had just before, and a local development of crystals would also almost certainly start convection. In the case of gas bubbles in a magma the escape of the gas from a crater lake would finally remove the cause of the circulation. In order to maintain the circulation there must be a continuous supply of gas bubbles to some portion of the magma. Similarly, if crystals settle out of a liquid magma they would no longer tend to move the liquid. The circulation caused by the density of crystals would be active only during the time in which crystals were developing locally in the liquid and settling through it. However, in a large body of magma either of these processes might be maintained for a long time.

THE DEVELOPMENT OF PHASES IN MAGMAS

Phases are defined in physical chemistry as the parts of a system which are mechanically separable. A simple magma consists of one liquid phase. Considered as a solution, the magma may contain various dissolved substances, including many minerals as well as gases and water; but it remains one phase and only one.

Gas phase.—When bubbles of gas separate from solution in a magma and remain in it as parts of a closed system (i.e., do not mingle with the outside air), they may be considered a second phase in the magma. The conditions and reasons for their separation are various. The solubility of gas in a liquid varies with the pressure. If a magma saturated with gas at a pressure of 200 atmospheres is erupted to the surface, where the pressure is one atmosphere, gas will separate from the solution. It is equally sure

[1] R. A. Daly, "The Nature of Volcanic Action," *Proc. Am. Acad. of Arts and Sci.*, XLVII, 76.

to separate if intruded in a region of less pressure, even if it does not reach the surface. The solubility of a gas also varies with the temperature and with certain changes in the composition of the magma. For example, the assimilation of other rocks or liquids may so change the composition as to make the gas less soluble. It becomes evident that gases may separate at considerable depth as well as at the surface.

Crystal phase.—It is a commonplace that a magma on cooling and under various modifying influences will crystallize in a series of mineral compounds. In the closed system, with some of the mother-liquor, each constitutes a phase.

New liquid phases.—The question of immiscibility in magmas may be left open. While it is not well to use the term as if the process were known, the discussion of probable cases would not be complete without the consideration of new liquid phases. Changes in temperature or composition are the explanations given for their separation.

FACTORS IN MAGMA MOVEMENTS

The points to consider in a discussion of convection are the forces applied and the viscosity and related effects tending to oppose or retard movement. We are not now concerned with the forces leading to the intrusion of magmas. The estimate of forces is wholly dependent on specific gravities and on the volume of the portions of different specific gravities. These must be estimated. The viscosity of magmas is known to be variable with composition, pressure, and temperature; and in the present case we must estimate the added effect of the presence of a second phase.

Viscosity.—The factor of viscosity is so great that by many the possibility of active convection in a crystallizing magma is dismissed as an absurdity; but the field evidence is strong enough to warrant a quantitative estimate. Furthermore there may be in the minds of many a misconception of the true nature of increased viscosity. A truly viscous fluid, as distinct from a weak solid, will yield to any small force if given time. Viscosity cannot inhibit the movement, but can only retard it. In a pitch a million of million times as viscous as water, stones will sink and cork will rise in a few weeks.

On the other hand, in as weak a solid as gelatine gas bubbles and small solids remain stationary indefinitely. Bowen's work on the settling of crystals[1] may be taken as evidence that a magma during crystallization is truly viscous. In such a liquid, then, any appreciable force applied is entirely sufficient to start action. It simply remains to estimate possible counteracting forces and the rate of motion likely to result.

It was estimated by Becker[2] that Hawaiian lavas were about fifty times as viscous as water (0.575 in C.G.S. units; water at 15°, 0.0115). Daly[3] estimates that rhyolites may be erupted at a viscosity of 11.5. Ranging from these values for actively moving magmas, we may be sure that on cooling the viscosity increases until in glasses it is almost infinite. Data connecting the viscosity with temperature are not available. Fortunately Bowen has noted the rate of settling of certain crystals and thus obtained some very useful estimates for viscosity *during crystallization*,[4] which is the condition of most importance rather than the actual temperature. His figures for probable maximum viscosities are 4 to 200 in C.G.S. units for melts ranging from basic to acid character, in which crystals are growing. Bowen calls these figures maxima because of the probable growth of the crystals during settling. Several factors tend to reduce the values in nature. The extreme fluidity actually shown[5] by intrusive magmas may be due to their retention of more water vapor than is the case in extrusive lavas. In agreement with this are the results of Morey[6] showing that fusions in the presence of steam show a remarkable decrease in viscosity. The importance of water in magmas is attested by hydrous minerals and miarolitic cavities in the rocks. On the other hand, some conditions may increase viscosity. Doelter found that pressure increased it, but

[1] N. L. Bowen, "Crystallization Differentiation in Silicate Melts," *Am. Jour. Sci.*, XXXIX (1915), 186.

[2] G. F. Becker, *op. cit.*, p. 29.

[3] R. A. Daly, "Mechanics of Igneous Intrusion," *Amer. Jour. Sci.*, XXVI (1908), 30.

[4] N. L. Bowen, "Crystallization Differentiation in Silicate Melts," *Am. Jour. Sci.*, XXXIX (1915), 186.

[5] A. Harker, *The Natural History of Igneous Rocks*, p. 223.

[6] G. W. Morey, "New Crystalline Silicates of Sodium and Potassium," *Jour. Amer. Chem. Soc.*, XXXVI (1914), 226.

added that 10,000 meters of rock would probably increase it no more than 30 per cent.[1] This estimate, like the others, may be modified 100 per cent or more by careful work, but may be taken as of the approximate order of magnitude. Applying this addition to Bowen's figures, we have as probable maximum viscosities in even figures 5 to 300 in C.G.S. units.

The effect of new phases remains to be considered. It may be assumed that moderate amounts of a gas or liquid phase will have little effect on the motion of bodies of magma. The accumulation of crystal phases, however, may give a decided difference in results. Direct data not being available, it is well to consider analogous cases. Curves have been drawn showing the effect of clay added to water and dilute water solutions. Though the increase in viscosity may be great in some cases, it is shown that a slip with 50 per cent solids may have a viscosity less than 10 per cent greater than that of water.[2] A rough test by the writer, with starch and rock powders of about 80 mesh, up to 25 per cent of volume, showed an increased bulk viscosity of less than 5 per cent. This would have little effect on the maxima above estimated. Bowen estimates that a magma may be eruptible even with 50 per cent crystals.[3] The maximum viscosities assumed in this paper will therefore be from 5 to 300.

The thermal gradient in magmas.—The variations in temperature in different parts of a magma during the cooling process have not often been estimated. Estimates of the thermal gradient in a magma occupying a chamber may be made from the calculations and assumptions of several authors, but they vary from 100° to 300°C.[4] Since it is here argued that convection would occur, let us assume that cooling occurs without convection, and calculate the forces tending to start such convection. For example, assume

[1] C. Doelter, *Physikalisch-chemische Mineralogie* (1905), p. 110.

[2] A. V. Bleininger, *U. S. Bureau of Standards Technologic Paper 51* (1915), pp. 25–30.

[3] N. L. Bowen, "Later Stages of Evolution of Igneous Rocks," *Jour. Geol.*, Supplement, December, 1915, p. 31.

[4] R. A. Daly, *Igneous Rocks and Their Origin*, pp. 224 and 258; A. Harker, *op. cit.*, p. 316; A. C. Lane, "Coarseness of Igneous Rocks," *Amer. Geol.*, XXXV (1905), 71; Ingersoll and Zobell, *Mathematical Theory of Heat Conduction*, etc. Ginn & Co., 1913.

that a magma at 1,300°C. may be intruded at a horizon a mile below the surface which may have a temperature not over 100°, average probably 50°. The heat loss can be calculated by the formula

$$Q=\frac{kAt(T-T_1)}{x},$$

where k is the conductivity in C.G.S. units, A the area in square centimeters, and $(T-T_1)$ the difference in temperature. So long as the surface of the earth was kept cool, the upward flow of heat would be fairly uniform until the magma cooled appreciably. On the other hand, the temperature at the floor will not remain uniform. The floor of the Duluth gabbro must have sunk nearly 10 miles. The isogeotherms would rapidly rise. The lava streams that fed the intrusion and even the approach of the magma chamber below would contribute to the rapidity of the rise. With these supplies of heat from below, the heat added to the floor by the gabbro would accumulate rather than pass on. A rough calculation by the same formula indicates that the gabbro added heat to its floor in a year equivalent to a general rise in temperature of 12° for the first mile. In 100 years the floor would be so hot that heat losses in that direction would be very small. The gabbro as a whole, however, would cool only a few degrees in 100 years. Thus it seems that by the time crystallization begins the loss of heat is likely to be from the top and sides of the chamber. If this loss occurred without convection—say from a zone 10 to 15 meters thick at the roof—this zone would be cooled 100° below the main body of the magma very soon, say within a month. In a few years the contrast in temperature would be much greater. It is therefore assumed that a difference in temperature of 100°C. in different parts of a medium to large magma is not unusual.

The specific gravities of phases.—Specific gravity varies with composition, temperature, and crystalline or glassy structure. Daly, in summarizing the results of several investigators, estimates that the change from liquid to crystalline rocks at the same temperature results in an increase of specific gravity as follows: 6 per cent for gabbros and diorites, 7 per cent for quartz-diorite, 8 per cent

for syenite, and 9 per cent for granite.[1] The data need confirmation, as authorities disagreed as much as 100 per cent. The difficulty of accurate estimates has been shown by Day, *et al.*[2] The expansion with temperature is estimated at 0.000025 volume per degree Centigrade, but is greater for liquids than solids.[3] From these one may roughly estimate the proper order of magnitude as given in Table I, though the figures may be far from accurate in detail. Attention is called to the small differences due to temperature alone as compared with larger ones due to a change from liquid to solid and to changes of composition.

TABLE I

APPROXIMATE SPECIFIC GRAVITIES OF PHASES IN MAGMAS

	At 1000°		At 1100°	
	Solid	Liquid	Solid	Liquid
Average Granite	2.63	2.40	2.62+	2.39
Quartz	2.60	2.37	2.59	2.36
Orthoclase	2.49−	2.27	2.48	2.26
Average Gabbro	2.92	2.75	2.91+	2.74
Plagioclase, Ab_6An_1	2.58	2.41	2.57	2.40
Plagioclase, Ab_1An_1	2.62−	2.46	2.61	2.45
Magnetite	5.05	4.80	5.03	4.77
Olivine	3.24	3.05	3.23	3.04
Augite	3.15	2.96	3.14	2.95

ESTIMATING CONVECTION EFFECTS

No formulas seem to have been developed which can be directly applied to the estimation of the rate of convection circulation. Daly uses an ingenious combination of calculations of (1) the rate of movement of small solid or gaseous spheres, (2) the size which is the limit of application of this formula, and (3) the relative rates for larger spheres.[4] The essential differences between such movement of spheres and convection are, first, that the magma moves

[1] R. A. Daly, "Mechanics of Igneous Intrusion," *Am. Jour. Sci.*, XXVI (1908), 27.

[2] A. L. Day, *et al.*, "Determination of Mineral and Rock Densities at High Temperatures," *Am. Jour. Sci.*, XXXVII (1914), 1.

[3] C. Barus, "High Temperature Work in Igneous Fusion," *U. S. Geol. Surv. Bull. 103.*

[4] R. A. Daly, *Igneous Rocks and Their Origin*, pp. 260–64.

as a larger mass than any sphere considered; and secondly, that the moving mass is not impeded by a liquid of uniform character, but on one side has a more viscous wall, while on the other side there is less resistance and some added tendency to move. On the whole, however, such a calculation may give a fair idea of the order of magnitude of the motion.

The rate of flow of liquids through a pipe may be compared with the rate estimated by this method. In comparison with the pipe, actual convection, though moving a larger volume of liquid, has the friction of only one solid wall. The evident error of estimating by settling spheres alone appears from the fact that a sphere of 10 meters radius gives the same rate in viscous as in less viscous magma. On the other hand, the formula for flow in a pipe gives too much weight to the matter of viscosity. The best idea is probably obtained from a consideration of both calculations and a comparison with the observed rate of convection in lava lakes.

Thermal convection.—On the basis of the data discussed above we may calculate the rate of settling of large spheres by reason of their greater density when cool.

Assumed temperature difference, 100°C.
Main magma specific gravity, 2.70
Cool magma specific gravity, 2.71
Density difference, .01
Final rate of motion of a sphere of 10 meters radius, nearly 1,000 meters per hour[1]

[1] The calculation for this rate of motion is given in detail for this case. Later estimates are made by the same method. If a small sphere sinks in a viscous liquid the final rate of motion is found by a formula of Stokes in *Trans. of the Cambridge Phil. Soc.*, IX, No. 2 (1850), p. 8.

$$x=\frac{2gR^2(d-d_1)}{9V},$$

where R is the radius of the sphere, d_1 the density of the liquid around it, g the acceleration of gravity, and V the viscosity. The largest sphere that will obey this law is calculated by a formula given by Allen in *Phil. Mag.*, L (1900), 324:

$$R^3=\frac{9V^2}{2gd(d-d_1)}.$$

For larger spheres the velocities are proportional to the square roots of the radii

$$\frac{x'}{x''}=\frac{\sqrt{R'}}{\sqrt{R''}}.$$

In the case of thermal convection, the second formula becomes

$$R^3=\frac{9(5)^2}{2(980)(2.70)(.01)}=4.2,$$

Gas-phase convection.—This case is covered by Daly.[1] He assumes from observations on vesicular lava at craters 200 "standard" (1 mm. at surface pressure) bubbles per cubic centimeter. At a depth of 3,000 feet a magma is under a pressure of 200 pounds per square inch. This is a greater pressure than some magmas are subjected to, but it is to be noted that the gas is not only compressed, but more soluble under pressure—a fact which Daly does not seem to consider. There should also be mentioned some thermal effects connected with the separation, reaction, and expansion of the gas bubbles; but too little is known of the effect of these factors on the density to include them in the calculation.

To obtain data comparable with those of other calculations in this paper the following case was selected:

Assumed pressure, 200 pounds per square inch
Assumed vesiculation, 200 "standard" bubbles per cubic centimeter
Magma specific gravity, 2.70
Vesiculated magma specific gravity, 2.638
Density difference, .062
Final rate of motion of a sphere of 10 meters radius, over 2,200 meters per hour.

Double liquid-phase convection.—If an intermediate magma splits into two immiscible liquids, consisting of granite and gabbro phases, the difference in specific gravity might be so great that a rapid separation of the two would occur; but it is not certain that the separation of immiscible globules is accompanied by any pronounced change in the aggregate specific gravity.

Crystal-phase convection.—The effects of the development of crystals should be emphasized, because of the certainty of the

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when the viscosity is 5. From this, $R=1.6$ cm. When R is 1.6 cm. and $V=5$, the Stokes formula becomes

$$x=\frac{2(980)(1.6)^2(.01)}{45}=1.1 \text{ cm.}$$

per second. For a sphere of 10 meters radius, the last formula

$$\frac{x'}{x''}=\frac{\sqrt{R'}}{\sqrt{R''}} \quad \text{becomes} \quad \frac{1.1}{x''}=\frac{\sqrt{1.6}}{\sqrt{1000}}.$$

From this $x''=27$ cm. per second. This is 972 meters per hour.

For the greater viscosity, 300, the radius R, of the sphere that will obey Stokes law, is greater, but the final rate of motion of a sphere of 10 meters radius is nearly the same as in the case of the lower viscosity.

[1] R. A. Daly, *Igneous Rocks and Their Origin*, pp. 261–64.

action of crystallization as compared with the separation of the gases and liquids in deep-seated magmas. All magmas crystallize before they are found exposed as deep-seated types, for geological investigation. During the process of crystallization important changes in the aggregate density are likely to occur locally, and the quantitative importance of the change may be estimated. It will be assumed for the calculation that the early crystals are of average density. The specific-gravity increase when crystallization occurs will be 6 to 10 per cent. As outlined above, the viscosity is not enough to interfere with eruption if 40 per cent of the mass is crystalline. To make a conservative estimate—

Assume that 20 per cent of the mass is crystalline.

On the crystallization of one-fifth of the magma the specific gravity of the aggregate will rise from 2.70 to 2.73.

The density difference for any magma is at least .03.

The final rate of motion of a sphere of 10 meters radius is nearly 1,700 meters per hour.

The mineral composition of the early formed crystals may now be included in the calculation. If magnetite crystallizes, the change in specific gravity is estimated as .26 (see Table I); for olivine and augite the change in specific gravity is .19. These, when compared with the change in average gabbro used in calculation (.03), indicate that if the early minerals are magnetite and olivine or augite the specific-gravity difference should be greatly increased, though the change in density of the residual magma would of course be in the reverse direction. With other contributing factors the specific gravity may change as much as .06—twice as much as was assumed. The rate of motion might be even greater than would result from deep-seated vesiculation.

Combination effects.—It is known that two minerals may crystallize together, and that gas may separate from a magma during crystallization; even the separation of immiscible fractions during crystallization is a possibility. These combinations may retard or reinforce the general convection tendency due to simple thermal changes in density.

Use of the formula for flow of liquids through pipes.—If a cylindrical pipe of 10 meters radius be imagined as bent approximately

square, with sides as long as the depth of the magma chamber; and further, if the liquid in one vertical side of the square is kept more dense than the rest, circulation will occur. The formula for viscous or direct flow is[1]

$$Q=\frac{(p_1-p_2)\pi R^4}{8Lv},$$

where Q is the quantity passing a certain place in unit time, (p_1-p_2) the difference in pressure, R the radius of the tube, L the length of the tube, and v the viscosity of the liquid. With a constant radius of 10 meters and the added relation that the length of the tube is 4 times that of the column giving the pressure, the formula reduces to

$$Q=\frac{d_1-d_2}{V}\times\frac{1{,}000^2}{8\times 4}\times\pi R^2=\frac{31{,}250\,\pi R^2(d_1-d_2)}{V},$$

where d_1 and d_2 are the specific gravities of the two upright columns.

The rate of flow can be derived from this by the quantity per second per unit cross-section:

$$x=31{,}250\frac{(d_1-d_2)}{V}$$

Comparison of estimates.—Tables II and III show the results in compact form.

TABLE II

ESTIMATED CONVECTION RATE, BY DIFFERENT METHODS, IN METERS PER HOUR

Viscosity (Water at .0115)	Phases	Settling Spheres	Flow in Pipe	Observed*
5	Hot and cool magma	1,000	2,200	.....
5	Magma and gas bubbles	2,500	12,000	2,000–5,000
5	Magma and average crystals	1,700	6,600	.....
5	Magma and heavy crystals	2,500	12,000	.....
300	Hot and cool magma	1,000	40	.....
300	Magma and gas bubbles	2,500	220	.....
300	Magma and average crystals	1,700	113	.....
300	Magma and heavy crystals	2,500	220	.....

* R. A. Daly records the convection in a crater lake as 2 to 5 kilometers per hour in "The Nature of Volcanic Action," *Proc. Am. Acad. Arts and Sci.*, XLVII, 76.

The calculated results in other columns are not strictly comparable, as they are based on a pressure of 200 atmospheres, and the convection in the crater may be more active than that 3,000 feet below.

[1] Poynting and Thomson, *A Text-book of Physics* (1902), p. 209.

A recent paper by W. K. Lewis, in *Jour. of Ind. and Eng. Chem.*, VIII, 627–32, gives a good statement of the present methods of calculation. For small velocities the formula for viscous flow applies even to pipes of large diameter.

The relative slowness of motion of sinking crystals is evident from a comparison of the tables. In a sill 1,000 feet thick a large crystal of olivine might settle in a day or two, though it is not probable; small ones would require a few weeks. Convection might carry them down in half an hour, or much less if the viscosity was not at a maximum.

TABLE III

ESTIMATED RATE OF FALL OF SETTLING CRYSTALS OF 4 MM. DIAMETER IN METERS PER HOUR

Viscosity	Mineral	Rate of Motion	Viscosity	Mineral	Rate of Motion
5	Magnetite	132	300	Magnetite	2.+
5	Olivine	25	300	Olivine	0.5
5	Augite	25	300	Augite	0.5
5	Plagioclase (rising)	13	300	Plagioclase (rising)	0.2

THE PROCESS OF SOLIDIFICATION WITH CONVECTION

Form and size and composition of magma.—Small bodies of magma are usually cooled to crystallization too rapidly to permit much circulation. However, the actual limit in size is not to be stated, as the fluidity and duration of crystallization may in case of abundant mineralizers allow an effective convection in a four-foot dike. Thin, tabular masses are unfavorable to any general circulation after intrusion is complete, but no special form or position of the mass seems to prevent all circulation. If the mass is nearly horizontal, settling crystals are more effective than circulation. It has been suggested also that thick, strikingly dome-shaped laccoliths assume their form because of unusual viscosity.[1] In so far as this is so they would be unfavorable to convection. The viscosity of a magma during crystallization depends largely on its composition. Data are not abundant, but indicate that viscosity is greatly reduced by dissolved gases such as water vapor; also that medium to basic magmas are less viscous than acid magmas.

Rate of cooling.—Aside from its size, the temperature of the mass and of its walls affects the rate at which the magma passes

[1] Sydney Paige, "Progressive Increase of Viscosity during Intrusion," *Jour. Geol.*, XXI, 541.

the stage of crystallization. If the cooling is rapid no convection of importance occurs. If the borders are chilled, convection can be active only in the central portions. In considering convection effects then, we eliminate all suddenly chilled phases. There remain many igneous masses of large size in which the process of crystallization extends over a long period.[1]

Where cooling occurs.—At first intrusion cooling progresses from all sides, but, as shown in the discussion of the temperature gradient, later cooling would be largely from the top of the mass and related to surface radiation and ground-water circulation. However, in a mass of laccolithic or batholithic form enough cooling would occur at the sides to establish normally some circulation. Once the current is established it tends to develop in power, the cooling top layer being drawn over to the sides as the side layers sink.

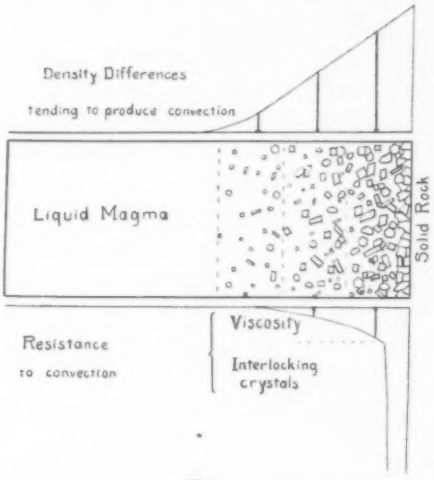

FIG. 1

The column of liquid which is effective in the motion is shown in Fig. 1, representing the zone of cooling near the side of the magma. The active force is much greater than the resisting viscosity up to the point where crystals begin to touch each other. It is greatest in a zone near the solidified wall. As crystallization progresses all the zones move inward. The width of these zones is wholly uncertain, but remembering the wide temperature range through which crystals may be in equilibrium with a magma, it seems probable that 20 meters (used in calculation) is a small estimate for large magma chambers.

[1] R. A. Daly, "Mechanics of Igneous Intrusion," *Am. Jour. Sci.*, XXVI (1908), 25.

The probable size of crystals in convection.—It is suggested[1] that if convection kept a supply of material at hand for the growth of a crystalline border, the largest crystals would be at the borders. This is actually the case in some pegmatitic differentiated dikes and indicates some movement in a thinly fluid magma. However, the mechanics of the process as outlined is not such as to furnish growing crystals a large supply of molecules from the central mother-liquor, though some such action may occur. The crystalline-border phase grows as a result of small crystals becoming caught in a more viscous, less rapidly moving wall. Here the progress of cooling is so advanced that, with the high viscosity, it is not to be expected that large crystals will develop.

The accumulation of crystals.—Most of the crystals, being heavier than the magma, would tend to settle; and though formed during the cooling along the top and sides of the chamber they would probably lodge at the sides and especially along the bottom during the forced circulation inward toward the rising current. Settling would here be entirely sufficient to remove crystals from the current. Similarly the crystals lighter than the magma would have a tendency to lodge along the roof and outer corners. Thus the segregation of minerals depends on gravity and is assisted by convection. It is largely independent of the place where cooling and crystal growth occur.

Orientation of crystals.—When a crystal once lodges in a viscous wall, too viscous to be again involved in general circulation, there may still be sufficient fluidity to allow orientation. The viscous matrix crystallizes, while the magma near it is still in motion, and the crystals would probably be oriented in the direction of the current—in most cases parallel to the walls of the chamber.

Gravity differentiation.—As most of the crystals of an igneous rock are heavier than the magma from which they grow, it will be expected that whichever forms first will segregate toward the bottom. It is only the coincidence of high gravity and early crystallization that results in a strict gravitative arrangement in the resulting rock. However, the general order of crystallization is, as a matter of fact, roughly the order of decreasing specific

[1] N. L. Bowen, "The Later Stages of the Evolution of Igneous Rocks," *Journal of Geology*, Supplement to Vol. XXIII (1915), p. 12.

gravity, and a gravitative arrangement is common. It is not to be expected that large segregations of a single mineral will be other than exceptional, because the cooling progresses in such a way that crystals of several minerals are likely to be growing at once and all settling together on the bottom as well as lodging along the walls. However, the conditions are easily conceived as possible for the formation of magnetite and peridotite near the base, and anorthosite near the top, of a single magma.

The behavior of immiscible liquids may be considered at this time. If the separation of globules occurred in a stationary magma, a gravitative rise and fall would tend slowly toward the separation of the fractions. If the immiscible liquids separate during convection, the smaller fraction, if light, will separate along the top, if heavy, along the bottom, as a fairly distinct layer in logical gravitative position. This layer may crystallize before or after the magma from which it separated, and the first to solidify may be intruded by the other. Abrupt gradations and contacts should be the rule. A small separated layer is likely to escape from the general circulation and is less likely to show a fluxion structure.

Double differentiation.—Thus it is conceived that a magma might differentiate into a series of bands dependent on the order of crystallization and settling, and *at the same time* give a rather abrupt gradation to a separated immiscible rock type—one of radically different composition. This is double differentiation. And the complexity of the sequence in some petrographic provinces is strong indication that two very different processes have been in operation.

Such a suggestion might apply to the occurrence of pyrrhotite at Sudbury which is said to have intrusive relations in some exposures to the main norite; and the norite itself is differentiated in roughly gravitative fashion.

Convection structures.—In discussing convection Pirsson makes the following suggestion: "Probably at first as the liquid moved inward over the floor of the laccolith and became reheated, these crystals [formed in the cooling border zones of the magma] would remelt, giving rise to numerous small spots of magma of a different composition, which would slowly diffuse."[1] It is noteworthy that

[1] L. V. Pirsson, "The Igneous Rocks of the Highwood Mountains," *U. S. Geol. Survey Bull. 237*, p. 188.

the result is, at least temporarily, a heterogeneous condition of the magma. Similar heterogeneity may result from crystals settling from an upper cooling zone into a deeper superheated zone. However, even more important variations in the magma are thought to result from the removal from the cooling zone of crystals of an early period of formation. Thus if a uniform magma had cooled on the outer edges of a laccolith until olivine crystallized, not only would there be convection due to the increased density of the olivine substance, but as the current moved along the floor some olivine crystals would settle out, leaving the liquid to rise in the central part of the mass with a different composition from the average.

It is important to consider in detail the result of this variation in the circulating magma. The material supplied by such a magma to the cooling border zone will differ from time to time and is almost certain to show some alternation because of a lack of rapid diffusion. As different material passed the cooling zone different crystals would be likely to develop, and a layer of different rock would be deposited on the walls and floor, giving rise to bands parallel to the current of magma and parallel to the walls of the chamber.

A further possible cause of alternation of materials deposited may be found in rhythmical activity of the cooling, or intrusion, or gas supply of the magma. Cooling is affected by annual and longer rhythms, but the depth of most of the igneous masses makes it unlikely that the rhythm from the surface would have notable effects. A rhythm in extrusive action is well recognized,[1] and the causes usually assigned to it would apply equally well to intrusive action. The supply of heat, gases, and lava may be distinctly periodic and may be responsible for the alternation of material crystallizing in the cooling zone of the magma.

Banding developed in this way is not likely to be perfectly regular, because of the irregularities of the current, its rise in the center, and its possible tendency to corrode or resorb some bands already deposited. Settling crystals on a large scale would tend

[1] J. D. Dana, *Volcanoes* (Dodd, Mead & Co., 1891), p. 124; Bonney, *Volcanoes*, pp. 274 ff.

to disturb the banding and give a gradation rather than an alternation in composition. It may be suggested also that stoped blocks settling in a magma would disturb such banding. Differentiation, however, is in no way interfered with[1] by the circulation that produces the banding.

SUMMARY

Several lines of evidence indicate that active convection occurred in many large, deep-seated magmas, and the process seems to be mechanically probable. In starting a current in such a mass the increase in density of growing crystals is probably more important than the development of any gas or separate liquid phases; and, added to the effect of simple cooling, the forces seem to be ample. Nearly all the field observations commonly made on igneous rocks may have a bearing on the question; probably first should be placed an alternation of bands of varying mineral composition; the position of the bands and the walls of the chamber; the mineral composition of the bands and the walls; any parallelism of grain and its direction; the form and size of the mass; grain variation near the margin; contact effects; the sequence of rocks formed in differentiation, continuous, double, or broken series; abrupt or gradual variations; intrusive relations between differentiates; gravitative or border position of differentiates; occurrence of one differentiate as a matrix for grains of another; the order of crystallization; signs of mineralizers, and their association with certain differentiates; globular forms.

The idea of convection becomes of practical service to the geologist when related to the banded structure. By it we may find the position of the walls of the chamber. The complexity of some differentiated rock series is best explained by assuming that some of the series developed during convection. Knowing the order of crystallization we can at once decide whether a mineral like magnetite is likely to be in bands near the bottom, or nearer the center, of the magma chamber. Finally a knowledge of the direction of the convection current aids greatly in estimating the extent of such a body of segregated magnetite.

[1] N. L. Bowen, "The Later Stages of the Evolution of Igneous Rocks," *Journal of Geology*, Supplement to Vol. XXIII (1915), p. 16, does not agree.

PERMO-CARBONIFEROUS CONDITIONS VERSUS PERMO-CARBONIFEROUS TIME

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Although the "red beds" of the late Paleozoic and other deposits of equivalent age have long been called Permian in North America, evidence is steadily accumulating to show that the true Permian is absent or nearly so, in the United States, and that the beds formerly so called are better regarded as of Permo-Carboniferous age.

Under one or the other of these names there have been included in the eastern part of the United States all the Paleozoic deposits above the base of the Dunkard formation in Pennsylvania, West Virginia, and Ohio, and possibly the upper beds of the Boston and Narragansett basins, the Paleozoic deposits of Nova Scotia and New Brunswick above the base of the New Glasgow conglomerate, and practically all of the red deposits of Prince Edward Island.

In the western part of the United States the same horizon is believed to begin with the base of the Elmdale formation of Kansas and its equivalents, both east and west of the Rocky Mountains.

The discovery of vertebrate fossils belonging to identical or closely related genera and the evidence of fossil plants have led to the suggested correlation of the red beds of Kansas, Oklahoma, Texas, and New Mexico with the Dunkard of Ohio and Pennsylvania, and the isolated deposits carrying vertebrate fossils near Danville, in Vermilion County, Illinois. Such suggestions of correlation, however, do violence to the probabilities indicated by the stratigraphic position of the beds in which the fossils are found. It is the purpose of this paper to point out what seems to be a more rational method of correlation, which will reconcile the evidence from fossils with that from the stratigraphy.

Correlation of widely separated horizons must be largely accomplished upon the evidence furnished by fossils, but, as is

becoming increasingly evident to all workers in stratigraphy as well as paleobiology, fossils must be regarded and interpreted as once living things, and the problem of their distribution is inextricably associated with the problem of their living conditions. The method of evolution is as yet undetermined, but all biologists concede the directive influence of environment when a line is once started, by whatever means it was originated. In other words, evolution of life follows and responds to change, or evolution, in the inorganic environment. If this be true, the beginning of a new geological interval of time is marked by the change in the inorganic world which will lead by slow degrees and a multiplicity of processes to the development, or immigration into a definite area, of new forms of life. The new interval begins with the establishment of new conditions fitted for the new life and may precede by a very considerable period of time the establishment of the new life in such abundance as to be recognized as constituting a new fauna, faunule, or flora. On the other hand, it is very possible that the establishment of new conditions may be almost immediately followed by the introduction of a new fauna or flora, as by immigration. These ideas are in strict consonance with the determination of geological intervals on the principle of diastrophism.

If any progressive criteria can be detected and traced which reveal such a change in the inorganic world, then the evidence of the organic world may be better interpreted and even in some measure anticipated. Changes in the inorganic world are in general more obvious under terrestrial conditions than under marine, but a change from marine to terrestrial conditions would be the most obvious of all.

The more evident and violent effects of diastrophism are readily detected and their results easily interpreted, but where the change is a slow and gentle one with slight disturbance of the rock layers and, as in a case of slow elevation, with a resultant destruction of the surface beds and sparse deposition of terrestrial sediments, the problem becomes far more intricate. In such a case it is sometimes necessary to turn to more obscure and commonly neglected factors, such as the climatic alteration resulting from change of altitude and exposure of large areas of land.

It is just this factor of climatic change that the author proposes to use in the interpretation of the change of environment in late Paleozoic and as a basis for the correlation of "Permo-Carboniferous conditions" as opposed to a correlation of a certain group of beds within definite stratigraphic limits. "Permo-Carboniferous conditions," as here used, involves the idea of an interval of time, but not of the same duration in all areas where such conditions prevailed, for, as will be shown, the conditions were developed progressively across a large area and the base of the deposits governed by such conditions cut obliquely across the stratigraphic column. In the case here discussed the shape of the deposits so governed is that of a flat wedge, for the conditions persisted where they were

FIG. 1.—Diagrammatic illustration of the relation of "Permo-Carboniferous conditions" to the late Paleozoic stratigraphy. No account is taken of the breaks or the present geological structures. The dashed area indicates "Permo-Carboniferous conditions."

first established and the progress of the conditions led to ever thinner deposits toward the outer limit (see Fig. 1). It is conceivable that under other circumstances a uniform set of conditions might pass across a large area as a wave, and the resultant deposits would then be detected in the stratigraphic column as a band of greater or less thickness oblique to the normal bedding-plane.

As shown in the abbreviated correlation table below, the Dunkard with its typical Permo-Carboniferous flora, fauna of invertebrates, and single characteristic vertebrate (*Edaphosaurus*) is by all commonly accepted canons of correlation and by its stratigraphic position the very approximate equivalent of the Wichita-Clear Fork beds of Texas, but both red beds and Permo-Carboniferous vertebrates are found far below this horizon in both Pennsylvania and West Virginia. In Pennsylvania, Raymond found vertebrates closely similar to those occurring in Texas in the Pittsburg Red Shale, 500 feet below the top of the

ABBREVIATED CORRELATION TABLE OF THE LATE PALEOZOIC

Texas	Oklahoma	Kansas	Indiana	Pennsylvania and West Virginia	Massachusetts	Rhode Island	New Brunswick
Absent or red deposits in the panhandle	Quartermaster and Greer	Cimarron		Dunkard	Roxbury conglomerate (Squantum tillite)	Dighton conglomerate	New Glasgow conglomerate
Double Mountain	Woodward	Wellington					
Clear Fork	Blaine	Marion					
Wichita*	Enid	Chase					
		Garrison	Merom sandstone				
		Waubunsee					
Cisco	Ralston (Chandler)	Shawnee	Coal VIII	Conemaugh	Dorchester slate	Rhode Island formation	Shulie formation

* Permo-Carboniferous conditions began approximately at the time indicated by the heavy lines in the table.

Conemaugh. In West Virginia, Hennen found the cast of a bone comparable only with *Pareiasaurus* in red shales about 200 feet below the base of the Monongahela series.

Dr. I. C. White has long contended that the sudden appearance of the red sediments in the Conemaugh marks the beginning of a new geological period with changed conditions of environment and sedimentation. The red deposits continue in Pennsylvania and West Virginia more or less dominantly to the top of the Dunkard. Farther to the north the red sediments, tillites of the Boston basin, the New Glasgow conglomerate and the red conglomerates, and shales and sandstones of Prince Edward Island are certainly well up in the late Paleozoic. Sayles and Mansfield have demonstrated the glacial origin of the Squantum tillite, and Bell has shown that the New Glasgow conglomerate is due to an elevation somewhere to the southeast.

These local proofs of elevation are but contributory evidence of the commonly accepted elevation of the whole eastern part of North America, probably as a continuation of the same movement which formed the Hercynian chain somewhat earlier in Central Europe. The elevation of North America which began on the eastern side was gradually extended to the west, as is shown by the progressive disappearance of the Mississippian sea and the Pennsylvanian coal swamps in that direction.

The elevation was attended by a gradual change in climate; instead of gray and black shales and white sandstones the prevailing deposits were colored red by the oxidation of the iron under the influence of a less equable climate, as seasons of relative drought and humidity succeeded each other.

As this climatic change migrated toward the west only slowly, red sediments were formed at progressively higher and higher levels. In western Kentucky, Indiana, and Illinois the conditions necessary for the formation of red beds did not arrive until after the highest sediments now preserved had been formed, or only thin deposits were formed which have since been removed by erosion. That the surface on these regions was dry land by the time "Permo-Carboniferous conditions" (formation of red beds) had reached them is suggested by the mode of occurrence of the vertebrates in Illinois and the Merom sandstone in Indiana.

Beyond the elevated region of Missouri the upper Pennsylvanian and Permo-Carboniferous rocks of Kansas are limestones and gray to black shales, but farther south the Permo-Carboniferous beds of Oklahoma, Texas, and New Mexico are red. These beds lie above the Missourian of Missouri and Iowa which extend well up toward the top of the Pennsylvanian, as developed in Pennsylvania and West Virginia, certainly much higher than the first appearance of red beds in the Conemaugh series in those states.

The appearance of red beds is generally accepted as evidence of a decided climatic change and it is also generally accepted that this change in the late Paleozoic was largely the result of an elevation of the continent which began in the eastern side and progressed toward the west, though other causes, as a change in the amount of CO_2 in the air, very probably had some part in the final result.

As stated above, red beds appear at successively higher levels toward the west. Detailed evidence for this will be given in a forthcoming monograph in the publications of the Carnegie Institution of Washington.

As the uplift affected regions farther and farther to the west, the climate altered progressively in the same direction and the resultant changes in physiography, hydrography, and vegetation compelled an alteration of the environment which permitted the migration of the Permo-Carboniferous reptilian-amphibian fauna with but little morphological change.

This environment remained fixed in the east as it spread westward, resulting in a wedge-shaped series of beds which can be correlated as formed under "Permo-Carboniferous conditions" from the observed effects produced by climatic factors. The wedge shape of this series causes it to extend deeply into the Pennsylvanian series (to middle Conemaugh) in the east and to involve only the true Permo-Carboniferous in the west. The development and migration of the vertebrate life were governed, not by the passage of geological time, but by the development and spread of the peculiar environment.

The occurrence of Permo-Carboniferous reptiles and amphibians much lower in the stratigraphic series on the east than on the west is no longer a puzzle. The animals appeared with the environment and migrated with it. They occur strictly within the time and

limits of "Permo-Carboniferous conditions" at every place where they are known.

The sequence in the evidence of the progressive development of the red bed westward is broken in two places by the elevation at the Cincinnati anticline and at the elevation in Missouri. An effort has been made to trace the beds around these elevations, but as yet with indifferent success. The breaks are in part due to the effects of erosion removing all traces of Permo-Carboniferous deposition and in part to the fact that these lands were elevated above the plane of deposition before the climatic migration had reached them.

An apparent conclusion from the premises here stated is that the Permo-Carboniferous vertebrate fauna originated in the eastern part of North America and migrated westward. This the author is not yet entirely ready to accept, and yet he is strongly impelled toward that conclusion by the facts that the earliest known reptile was discovered in the Allegheny series, at Linton, Ohio; that typical Permo-Carboniferous vertebrates appeared in middle Conemaugh time in Pennsylvania and West Virginia, and that typical Pelycosaurs occur in the red beds of Prince Edward Island at a stratigraphic level much lower than those of Oklahoma and Texas.

The theses of this paper are:

1. That environment is the determinant factor in the development and spread of a fauna.

2. That an environment favorable to a certain group may develop and migrate, involving different levels of one or more geological epochs.

3. That a fauna or flora may be correlated as belonging within the limits of such an environment independent of stratigraphic levels.

4. That the limits of such an environment may be detected by various lines of inorganic evidence. In the case of the development and spread of "Permo-Carboniferous conditions" the effect of climate furnishes the observable limits.

Further evidence for the statements made in this paper and more extended treatment of the subject will be given in a monograph of the Carnegie Institution of Washington dealing with the environment of life in the late Paleozoic.

NOTES ON THE GEOLOGY OF EASTERN GUATEMALA AND NORTHWESTERN SPANISH HONDURAS[1]

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FIG. 4.—Map of the eastern portion of Guatemala.

INTRODUCTION

The geology of Central America between the Isthmus of Tehuantepec and the line of the proposed Nicaragua Canal has been known only from the researches of Dr. Karl Sapper. These observations through a number of years have covered a vast amount of territory in a general way.[2] A brief examination of the Atlantic

[1] Published by permission of the Director, United States Geological Survey.

[2] K. Sapper, "Über Gebirgsbau und Boden des nördlichen Mittelamerika" (with geological map of Guatemala), *Peterm. Mitt.*, Ergänzungsheft 27, Heft 127, 1899; "Gebirgsbau und Boden des südlichen Mittelamerika" (with geological map of

Coast region between Trujillo, Spanish Honduras, and Livingston, Guatemala (Fig. 1), forms the subject of the few notes on the geology which are here presented. The petrography of the igneous rocks collected in Honduras is described in an accompanying paper by Professor Wilbur G. Foye, of Middletown, Connecticut.

Geologic investigations in the portion of Central America examined are conducted with difficulty owing to the primitive means of transportation inland beyond the coastal banana-plantation railroads and to the dense growth of tropical vegetation. Satisfactory exposures are confined to stream valleys. Also a scarcity of fossils in pre-Tertiary strata makes correlation and age determination exceedingly difficult. In Honduras fossils of Triassic and Cretaceous ages have been described; in Guatemala strata of Carboniferous (probably Pennsylvanian or upper Mississippian), Cretaceous, Eocene (?), Oligocene, Pliocene, and Pleistocene ages are known.[1] A lack of fossils and of detailed knowledge of the metamorphic rocks has made it impossible to determine whether they are in large part merely a metamorphosed portion of the Carboniferous or of an earlier Paleozoic system, as is suggested by the writer, or whether they are of pre-Cambrian age, as supposed by Sapper.

GENERAL GEOLOGY

Eastern Guatemala and northern Honduras lie on the south and southeast sides of the V-shaped Gulf of Honduras in latitudes 15° to 17° N. Commencing at the north the larger portion of the peninsula of Yucatan (Fig. 1), with the exception of the Cockscomb Mountains (an outlier of Paleozoic rocks in British Honduras), is composed of horizontal sediments of late Tertiary age which

Honduras and Central America), *ibid.*, Ergänzungsheft 32, Heft 151, 1906; "Grundzüge der physikalischen Geographie von Guatemala," *ibid.*, Ergänzungsheft 24, Heft 113, 1894–95; "Die Alta Verapaz" (Guatemala) (with geological map of part of Guatemala), *Mitt. Geogr. Gesell. Hamburg*, XVII (1901), 78–224; "La geografía física y la geología de la península de Yucatán" (Chiapas and Tabasco states only), *Bol. Inst. geol. México*, No. 3, 1896; A. Dollfus et E. de Mont-Serrat, *Mission scientifique au Mexique et dans l'Amerique Central, Géologie*, Paris, 1868; E. Suess (de Margerie), *La Face de la terre*, III (3) (1913), 1264–74.

[1] Bailey Willis, *Index to the Stratigraphy of North America*, U.S. Geol. Surv., Professional Paper No. 71, 1912.

form a region of little relief. A belt of gently folded Cretaceous and Oligocene strata, principally limestones with an east-west trend, separates the lowlands on the north from the high mountain ranges in the south. The relief of the mountains carved in rocks

FIG. 1.—Tectonic lines in Honduras and Guatemala, modified from Sapper (Eighth International Geographical Congress, 1904 [Washington, 1905], Fig. 1).

of these ages is of the order of 1,000 to 2,000 feet. Mountains of metamorphic and intrusive rocks forming conspicuous parallel ranges extend from southwestern Mexico and central Guatemala through northern Honduras and meet the coast at an angle on the south side of the Gulf of Honduras. The relief of the mountains

is 1,000 to 4,000 feet and the height of some more than 5,000 feet.[1]

Plateaus and irregular ridges of low relief, but with elevations of 3,000 to 4,000 feet, are found west and southwest of the mountains composed of metamorphic rock. This region is composed of early Tertiary or possibly late Mesozoic volcanics.[2] In places folded sedimentary rocks appear with the volcanics. Farther inland and nearer the Pacific Coast the ridges of folded volcanics give way to broad plateaus that are 3,000 to 4,000 feet above sea-level and are separated more or less completely from one another by rims of low hills. The plateaus slope gently toward the east. Young, deep gulches are rapidly dissecting the plateau surfaces. Exposures thus made show that the surfaces were formed in an earlier cycle of erosion by overloaded streams under conditions of aridity and that deep incision is now taking place for the first time. The summit of the plateau forms the continental divide—a volcanic plateau on which stands Guatemala City at an elevation of 4,900 feet.

On the Pacific slope in Guatemala the high plateaus are bounded by a row of active and recently extinct volcanoes which rise in many cases directly to elevations of 10,000 to 13,513 feet from the low plain that forms the coast. The alignment of the volcanoes is parallel to the coast and diverges sharply from the trend of the older mountain ranges. The plain at the coast is composed of volcanic ejectamenta and shows no signs of uplift; hence it would not be called a coastal plain according to some definitions of that term. It is so level that 20 miles inland, at Santa Maria, the elevation is only 416 feet. From here the surface gradually rises to an elevation of 1,100 feet at Escuintla, 27 miles inland. Only 40 miles inland the dormant volcano Agua, near Escuintla, is 12,140 feet high.

[1] Elevations of 8,000 feet for Congrejal and Bonita peaks, near La Ceiba, Honduras, as given on a chart of the U.S. Coast and Geodetic Survey, evidently should be 4,000 feet.

[2] Vulcanism is thought to have begun during the Eocene in Mexico (J. G. Aguilera, *Compte Rendu* [10th Int. Geol. Cong., Mexico, 1906], p. 1157) and to have been in progress during the Oligocene in Nicaragua (C. W. Hayes, quoted by Sapper, *Zeit. Ges. f. Erdkunde* [Berlin, 1902], p. 513).

Rainfall and humidity have everywhere an important bearing on vegetation and therefore on surface features. The high plateaus behind mountains which catch all the moisture suffer from aridity and afford scant vegetation. At lower elevations, but again in the lee of the mountains, there are deserts, as at Zacapa, supporting only cactus. Near the sea both coasts receive an overabundance of rainfall with accompanying great humidity. On both sides of the Isthmus the northeast trades are the prevailing winds, but on the Pacific Coast the winds are variable except during winter of the northern latitudes.

Statistics for an average year show rainfall on the Pacific Coast (elevation 600 feet) of 240 inches; at Guatemala City (elevation 4,900 feet) of 60 inches; at Quirigua (elevation 240 feet), 57 miles from Puerto Barrios, but behind a mountain range, of 99 inches; at Panzos (elevation 50 feet), 100 miles inland, of 115 inches; at Puerto Barrios, on the Atlantic, of about 200 inches. The rainy season on the Pacific Coast is May 15 to October 15, on the Atlantic Coast June 15 to August 15 and September 15 to February 15. The best weather in Guatemala and Honduras as a whole is therefore in the winter and spring of the northern latitudes, and only during this dry season can geologic work be carried on satisfactorily in the coastal regions.

GEOLOGY

Spanish Honduras.—Northern Honduras consists of two mountain ranges of the metamorphic series, each with many subsidiary branches. The first of the parallel ranges forms a portion of the boundary line between Guatemala and Honduras (Figs. 1 and 4) and is variously known as the Sierra de la Grita, Sierra de Merendon, Sierra del Espiritu Santo, and the Sierra de Omoa—the Omoa Mountains. This range lies for a distance between the Motagua and Chamelecon rivers (Fig. 2), but east of the broad Chamelecon-Ulua lowlands it reappears in Punta Sal and in the Bay Islands (Utilla, Ruatan, and Bonacca). The second range, Sierra de Pija (Fig. 1), lies west of the Ulua River between the various short streams on the Atlantic shore and the Aguan River (Yoro-Olanchito) valley. This range extends into the sea east of Trujillo.

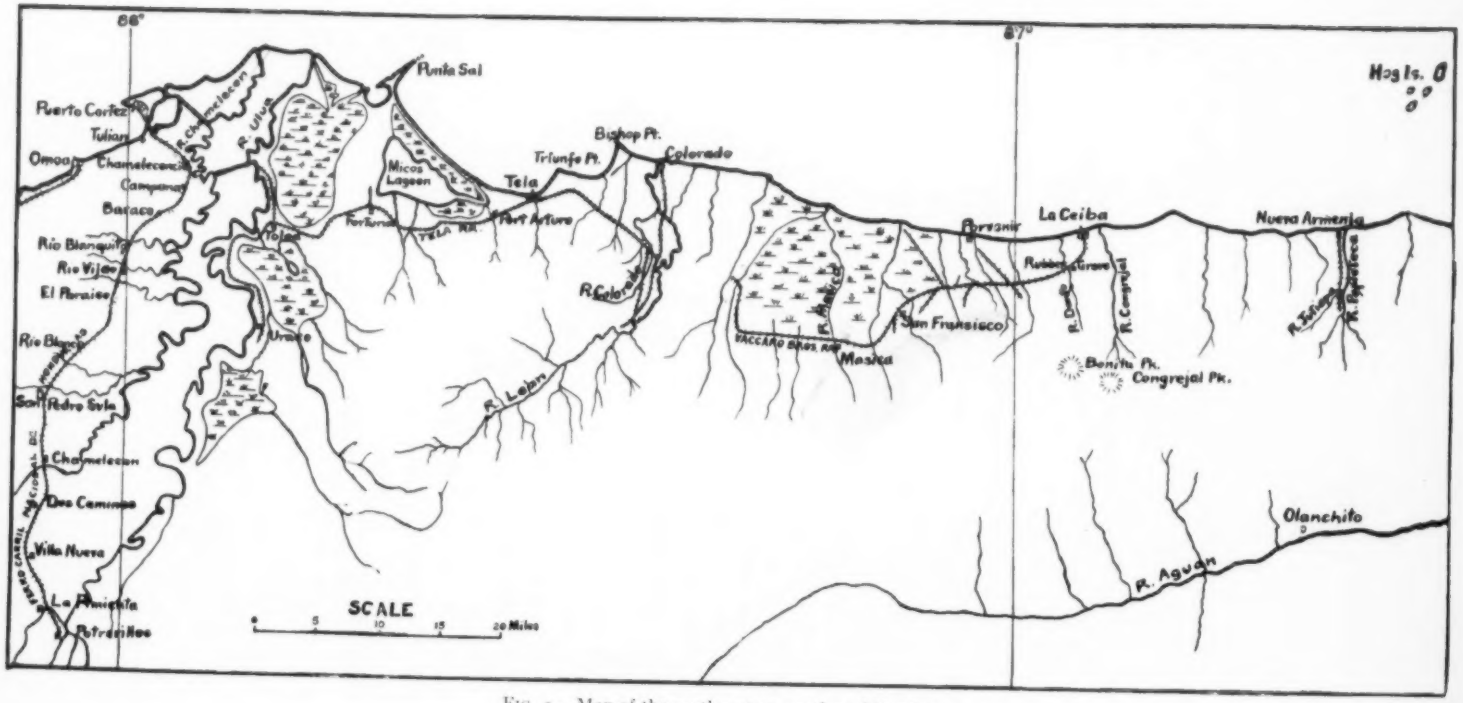

FIG. 2.—Map of the northwestern portion of Honduras

Considered as a whole, the Omoa Range consists principally of slates, schists, quartzites, and limestones, while the Sierra de Pija is composed of mica schists and quartzites intruded by granodiorites, diorites, and tonalites.[1] The igneous rocks as a whole may represent phases of a single large batholith. The intrusions have a lineal arrangement in a N. 50°–80° E. direction and occupy the region between the sea and the summit of the range. Basalt of Tertiary or Quaternary age occurs in the Sierra de Omoa at Chameleconcito, near Puerto Cortez, and on the island Utilla. Sandstones and conglomerates of late Tertiary age are found along the shore cliffs between Puerto Cortez and Omoa.

The age of part of the metamorphic rocks is known to be Paleozoic; the age of the remainder is thought to be Paleozoic. Carboniferous fossils were found by the writer in metamorphosed, horizontally bedded limestones in the hills west of Puerto Barrios, Guatemala, not far from the line of strike of the marbles in the Sierra de las Minas, north of the Motagua River valley, and of other metamorphic rocks. If the metamorphic rocks are of Paleozoic age the batholithic intrusions must have appeared during the subsequent folding, presumably at the close of the Paleozoic.

Along the continuation of the Sierra de Omoa at Punta Sal, north of Tela (Fig. 2), black slates striking N. 70° E. and dipping 55° N. form a prominent ridge. The main range of the Sierra de Omoa consists of mica schists, quartz schists, and quartzites, as seen in the exposures along the Ferrocarril Nacional de Honduras between Chameleconcito and Baracoa. Limestone appears at Baracoa, where springs of cool carbonate water have built large calcareous tufa terraces. At Rio Vijao marble has been quarried for ballast. The marble may be seen as far as Rio Chaloma (El Paraiso), but is replaced by tonalite or granodiorite from this point to San Pedro Sula. No observations were made on the Sierra de Omoa near the Guatemala boundary, but at Quebradas de Oro, in Guatemala, placer gold is mined hydraulically, the country rock being hornblende schist penetrated by quartz veins.

[1] Described in "Notes on Collection of Rocks from Honduras, Central America," by Wilbur G. Foye, in this issue of the *Journal of Geology*.

Gently folded Tertiary or possible early Pleistocene sand, gravel, and clays are exposed in sea cliffs 40 feet in height between Tulian, south of Puerto Cortez, and Omoa. Bedding in these sediments is on the whole regular, but within individual strata there is cross-bedding. The gravel is composed in part of bowlders 3 inches to a foot in length, packed together as if deposited in streams and not in the sea. No shells or fragments of wood were found, although in somewhat similar beds at Livingston, Guatemala, casts of marine shells of Pleistocene (?) age were found.

Olivine basalt composes a number of small, rounded hills one mile south of Chameleconcito and near the National Railroad. The hills are of the typical form developed on weathered *aa* flows. A recent, perhaps Pleistocene, age must be assigned to the basalt flows here and on Utilla Island.[1] Hot springs, apparently connected with the same vulcanism, are very common along the coastal region from the Gulfete (Rio Dulce), Guatemala, to Trujillo, Honduras, especially near the foot of the mountains between Tela and Trujillo.

Between the Sierra de Omoa and the Sierra de Pija in the vicinity of the National Railroad tonalites appear in low hills north and west of San Pedro Sula. This city is built on a broad gravel fan extending from the mountains on the south. In these mountains the contact effect of diorites with metamorphosed schists may be seen. A tonalite similar to that exposed near San Pedro Sula outcrops in the Ulua River and in the hills near Uraca, a native village at the present southeastern terminus of the Tela Railroad, 36 miles by rail from Tela. From Uraca eastward diorites, tonalites, and other igneous rocks invade schists and quartzites, as described by Professor Foye.

[1] The distribution of the basalt is in accord with the researches of A. Bergeat ("Zur Kenntnis der jungen Eruptivgesteine der Republik Guatemala," *Zeit. d. d. Geol. Gesell.*, XLVI [1894], 131–57), who shows a conspicuous arrangement of volcanics according to types in the few specimens of Guatemalan volcanics examined. Basic and acidic types, basalt and rhyolite, are practically confined to the region east of the Pleistocene volcanoes, while the intermediate type, andesite, is the conspicuous component of the surficial rocks of the Pacific volcanoes. A predominance of volcanics of an intermediate type on the immediate borders of the Pacific Ocean is also suggested by B. Koto to hold true in Japan (*Jour. Geol. Soc. Tokyo*, XXII [1915], 124; XXIII [1916], 127).

South of San Pedro Sula, at Chamelecon, intensely folded mica schist is exposed. The foliation strikes N. 80° E. South of Chamelecon and of the Chamelecon River, crystalline limestones, in which no trace of bedding or of fossils were found, extend from Dos Caminos to Potrerillos, the terminus of the National Railroad. One mile south of La Pimienta the limestone is overlain by volcanic ash and by lava flows. Sapper maps the limestone as Upper Cretaceous.[1]

In the Sierra de Pija between the Ulua River and Trujillo igneous and metamorphic rocks were found in every stream examined. Tonalites and porphyries are the most common igneous rocks, with paleovolcanics on the west, especially in the vicinity of La Ceiba and in the Congrejal Valley south of La Ceiba. The metamorphic rocks of sedimentary origin are schists and slates with cleavage striking N. 60° E. parallel to the range.

The Bay Islands, lying 20 to 35 miles off the north shore of Honduras, consist of three large islands, Utilla, Ruatan, and Bonacca (Fig. 1), with several small islands and cays. While the axes of the large islands are not quite parallel, they are all part of the Sierra de Omoa. Historically the islands are known from the fact that Columbus landed on Bonacca on his fourth voyage in 1602, and from the fact that they are inhabited by English-speaking people and were not ceded to Honduras by Great Britain until 1860.

Bonacca Island is 10 miles long and $2\frac{1}{2}$ miles in maximum width, and the highest elevation is 1,200 feet. According to Sapper the island is composed of mica schist with serpentine (marble?) on the western end. Ruatan is 33 miles long, 3 miles wide, and the highest elevation is 800 feet. Sapper found mica schist with some crystalline limestone and amphibolite on the island.[2] Utilla is $7\frac{1}{2}$ miles long and $2\frac{1}{2}$ miles wide. The western two-thirds of the island is composed of coral reefs, lagoons, and swamps, but the eastern third consists of a rolling upland averaging 40 feet in height, surmounted by Pumpkin Hill, 290 feet high, and Stuert Hill, 169 feet high. The rolling surface is underlain by olivine basalt flows.

[1] *Peterm. Mitt.*, Ergänzungsheft 32, Heft 151 (1905), geologic maps.

[2] *Ibid.* (1905), pp. 17–18.

Stuert Hill consists of olivine basalt and agglomerate. Pumpkin Hill of palagonite tuff of basaltic composition containing fragments of coral reef limestone. The tuff with its inclusions is indistinguishable from that which composes the well-known cones on the island Oahu, Hawaiian Islands, near Honolulu. Stuert Hill was evidently

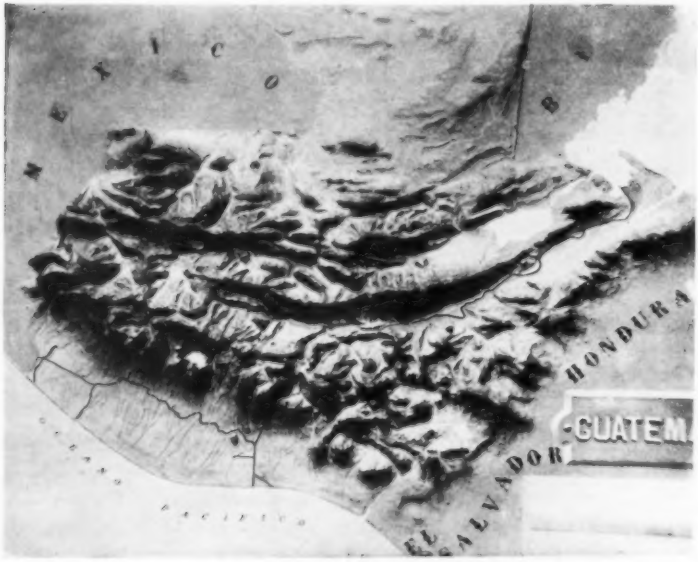

FIG. 3.—Relief map of Guatemala, showing the long Polochie–Lake Izabal Valley on the north, Motagua Valley in the center, the row of volcanoes facing the Pacific, and the broad plain at the Pacific Coast. The International Railroad runs from Puerto Barrios, on the Atlantic, up the Motagua Valley, past Guatemala City in the high plateaus to San Jose, on the Pacific. A branch line runs from Santa Maria northwestward to the Mexican boundary.

a center of volcanic activity in Quaternary time—perhaps the principal one for the island—while Pumpkin Hill probably resulted from a local submarine eruption breaking through coral reefs. Small coral reefs are found on the summit of Stuert Hill, and a small elevation called Brandon Hill is composed entirely of limestone. The age of these reefs is unknown, but is probably quite

recent. The only evidence of pre-Tertiary rocks on the island found by the writer was a block of mica schist in the cemetery. The Hog Islands, near Nueva Armenia, at the mouth of the Paploteca River, are composed, according to Sapper, of mica and graphite schist.[1]

Guatemala.—A relief map of eastern Guatemala (Fig. 3) shows two remarkable east-west valleys, the Motagua and the Polochie–Lake Izabal, separated by the Sierra de las Minas range, which follows a curve slightly concave to the north. The region south

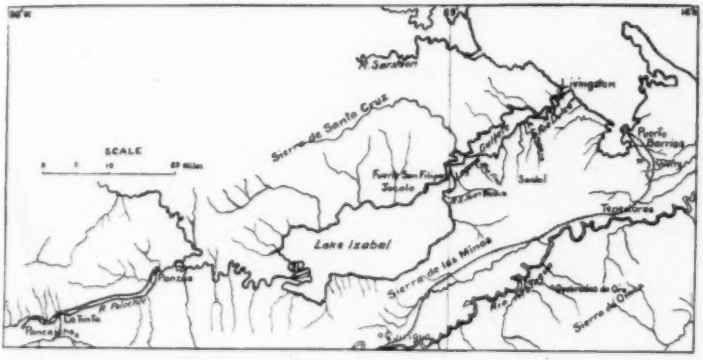

FIG. 4.—Map of the eastern portion of Guatemala

of the Motagua Valley is formed by the continuation of the Sierra de Omoa. The Sierra de las Minas is composed of sedimentary and metamorphic rocks of Carboniferous and of pre-Carboniferous age. North of Lake Izabal the rugged country of gradually diminishing relief is underlain by folded limestones of Cretaceous age.

Fossils of Carboniferous age were collected by the writer in two localities: in the mountains west of Puerto Barrios along the pipe line to the reservoir which supplies that town, and on the line of the Panzos Railroad, along the south bank of the Polochie River near Pancajche, the western terminus of the line (Fig. 4). At the former locality poorly preserved fossils were found in weathered surfaces of a massive, bluish limestone which is metamorphosed and cut by innumerable calcite veins averaging one-quarter of an

[1] *Peterm. Mitt.*, Ergänzungsheft 32, Heft 151 (1905), pp. 17–18.

inch in width. The age of the fossils was determined by Dr. E. O. Ulrich as probably Upper Mississippian or Lower Pennsylvanian. Excellent exposures of the same rock were seen in a quarry 7 miles inland from Puerto Barrios along the old line of the International Railways of Central America. The Pancajche fossils, a large species of *Fusulina*, of Pennsylvanian age according to the determination of Professor P. E. Raymond, were found in dense, bluish limestone interbedded with slate and with mica schist dipping 40°–80° S. to S.E. These rocks belong to the Santa Rosa formation of Sapper.[1]

The Sierra de las Minas range is mapped by Sapper[2] as being composed, from south to north, of serpentine, crystalline schist and gneiss, granite (in part of range), Santa Rosa formation schist of Carboniferous age (as at Pancajche), and Carboniferous limestone. The belt mapped as serpentine coincides with a belt of very good quality white, crystalline marble which composes the south flank of the mountains and is now being quarried on an extensive scale 15 miles northwest of Zacapa (Fig. 1). The marble is said to be equal in quality to any in the United States.

An unconformity is supposed to exist on the north side of the mountains between the crystalline rocks and the fossiliferous Santa Rosa formation schists. The evidence of this unconformity is stated by Sapper to be the presence of occasional pebbles of crystalline schist as large as nuts in the Santa Rosa schists.[3] On the strength of this evidence Sapper places the crystalline schists in the pre-Cambrian, although he admits that the rocks cannot always be distinguished. Confirmatory evidence of the existence of this unconformity is needed, for the degree of metamorphism of the rocks increases from north to south in both Guatemala and Honduras. Mountain-building movements at the close of the Paleozoic will account for all the variations in the degree of metamorphism of the Paleozoic rocks. Intensely metamorphosed and recrystal-

[1] *Mitt. Geogr. Gesell. Hamburg*, XVII (1901), with lists of fossils collected by him.

[2] *Peterm. Mitt.*, Ergänzungsheft 27, Heft 127, 1899; *Mitt. Geogr. Ges. Hamburg*, XVII (1901).

[3] *Mitt. Geogr. Gesell. Hamburg*, XVII (1901); Dollfus et Mont-Serrat (*op. cit.*) also report an unconformity.

lized rocks such as would be expected in a pre-Cambrian terrane are absent.

A block of almost horizontally bedded uppermost Oligocene limestone forms a flat-topped ridge 3 miles wide at Livingston. This block was probably faulted down against the Carboniferous limestones of the Puerto Barrios reservoir during the late Miocene folding of the region, but its present width may have been determined by later movements. Through this block the Rio Dulce cut a narrow gorge during the latest uplift of the region; the gorge is 300 to 500 feet in width and 175 to 300 feet in depth. The fauna collected in the walls of the gorge consists principally of corals and oysters, but it is not a coral-reef formation.[1]

Oligocene limestone, which may be called the Rio Dulce limestone, is undoubtedly more widespread in northern Guatemala than has hitherto been supposed. Limestones forming low hills on the north shore of Lake Izabal at Jocolo (Fig. 4) with a N. 50°–80° E. strike and apparently vertical dip resemble the Rio Dulce limestone lithologically and in obscure fossil content. Likewise blocks of limestone collected at Fuerte San Filipe, at the entrance to Lake Izabal, show spines and other fragments of echinoids on weathered surfaces and are probably part of the same formation. As Sapper mapped the Livingston–Sierra de Sta. Cruz region as Upper Cretaceous,[2] part of his extensive Cretaceous area may be of Tertiary age.

Slightly consolidated quartz gravels and clays containing casts of marine shells of Pliocene or Pleistocene age are found in the lowest of the terraces on which Livingston is built. These gravels are probably a part of the formation which is exposed along the Omoa and Tulian shore of Honduras, as already described. No evidence of folding was seen, however, in the Livingston exposures. Fossiliferous white clays containing chert pebbles and interbedded black lignite seams of Pleistocene or possible Pliocene age underlie the region between Sanhil (Sierra de las Minas), the Rio Dulce

[1] Dr. T. W. Vaughan, of the U.S. Geological Survey, identified the fragmentary fossils as resembling those of the Emperador limestone of the Canal Zone (the Empire limestone of R. T. Hill).

[2] *Peterm. Mitt.*, Ergänzungsheft 27, Heft 127 (1899), geologic map.

limestone ridge at Livingston, and Lake Izabal (Fig. 4). The fossils collected were identified by Dr. Paul Bartsch as the fresh-water gastropod *Sphaeromelania lacustris* Morelet (?).[1] Lignite beds 2 to 3 feet thick occur in several streams emptying from the south into the Gulfete and Laguna between Rio Dulce and Lake Izabal—Rio Lampara, Rio Frio, Rio Juan Vicente—and lignite beds are reported near Livingston east of the Rio Dulce limestone. The white clays and lignite beds may have a thickness of a few hundred feet. They are folded, dips as high as 8 degrees being observed. Rounded chert bowlders, apparently similar to those associated with these clays, are reported by Sapper to be associated with chalk and limestone in northern Yucatan and in British Honduras between Belize and Orange Walk.

British Honduras.—Southern British Honduras is underlain by a continuation of the Oligocene Rio Dulce limestone and of the Cretaceous limestone of Guatemala. Prominent ridges of limestone, probably the Rio Dulce limestone, form the hills along the Sarstoon River near the southwest corner of British Honduras and at Punta Gorda, British Honduras, on the coast. North of Punta Gorda the flat shore is bounded by the most extensive barrier reef in the Atlantic Ocean. Behind the cays and reefs is the closed inland passage up the Yucatan Coast with narrow channels through the reefs. Farther north the large island Cozumel, composed of limestone reefs elevated 10 to 30 feet above sea-level, lies off the flat, monotonous coast of Yucatan.

Geological observations on British Honduras have been made by Sapper and by others.[2] The Cockscomb Mountains of British Honduras are described as a horst about 45 miles in diameter with mountains as high as 3,050 feet. Sapper speaks of granites and quartz porphyries, argillaceous schists, quartzites, and crinoidal Carboniferous limestone striking in a northeast to east direction. North of these mountains and extending over the large department Peten, Guatemala, late Tertiary limestones are so soluble that the

[1] Collected near Rio Frio. From shells eaten by the Indians Dr. Bartsch identified *Euglandina carminensis* Morelet, *Sphaeromelania corvina* Morelet, *S. glaphyra immenis* Morelet, and *S. glaphyra* Morelet.

[2] *Peterm. Mitt.*, Ergänzungsheft 27, Heft 127, 1899; E. Suess (de Margerie), *La Face de la terre*, III (3) (Paris, 1913), pp. 1264–74.

drainage is largely underground. One cave on the Belize River is said to rival the Mammoth Cave in size.

RECENT CHANGES OF LEVEL

A stillstand of the Central American coast is scarcely possible, as is indicated by the frequent earthquakes which disturb the country. In Guatemala perceptible earthquakes are frequently of daily occurrence on the high plateau, as at Guatemala City, but are relatively rare on the Atlantic shore. Changes of level are recorded along the Atlantic shore in elevated coral reefs and terraces and in drowned valleys.

Evidence of uplifts are seen on Utilla Island. A coral reef covers the summit of Stuert Hill, 169 feet high, and less conspicuous reefs are found at lower levels, the lowest being a recently elevated reef 3 feet high on the eastern side of the island. The same recent uplift may account for the narrow bench in front of a wave-cut cliff of basalt on which the town Utilla has been built. Extensive coral reefs and cays surround Utilla Island, but they nowhere skirt the mainland of Honduras or Guatemala in the regions examined.

Lagoons fronted by a continuous sandy beach skirt the northern coast of Honduras. The beaches are tied to rocky headlands and to river deltas, but they extend across the mouths of rivers in the form of bars 2 to 6 feet in depth. A normal tide of only about one foot and littoral currents from west to east have favored the construction of the bars. No vertical movements are connected with their formation.

Elevated benches obscured by dense vegetation probably occur all along the coast, but these benches are evidently not very recent, as they lack well-defined facets toward the coast except at Livingston and near Puerto Cortez. At Livingston, Guatemala, the town is built on terraces 35 and 55 feet in height. Across the bay from Puerto Cortez, at Tulian, distinct 40- and 60-foot terraces were seen. No corals or marine shells were found on any of these terraces. Shells are common on the present beach, but coral fragments are absent.

Evidence of earlier subsidence in both Honduras and Guatemala was seen in the broad river valleys filled with alluvium in which the

streams are now cutting narrow channels, and in the terraces along the continental shelf. Coast charts show a shelf about 5 miles wide with terraces at depths of about 15 and 30 fathoms in the vicinity of Utilla Island. The antecedent stream, Rio Dulce, Guatemala, flows through a rock gorge, and the depth of the water through the gorge and directly behind the bar is 40 feet. No other stream along the coast has a rock bed at sea-level. Therefore data on subsidence are very fragmentary.

TECTONICS

Guatemala and Honduras are composed of two mountain systems (Fig. 1): the Pacific Cordillera, now little more than a belt of high plateaus covered with young volcanics, and the Caribbean Cordillera, consisting of east-west ranges. On the north the tectonic lines of Yucatan trend toward the Isle of Pines; in the center of Guatemala they trend toward a 3,000-fathom deep; on the south, in Honduras, they trend toward Jamaica. The two systems are in striking contrast; from the Atlantic, broad, structural valleys with a maximum length of 200 miles (Fig. 3) stretch almost across the Isthmus; from the Pacific, short, precipitous valleys extend to the high plateau between the volcanoes and almost disappear on the low plain near the coast.

It has been pointed out above that successively older formations appear on the Caribbean side of the Isthmus from north to south and that the Tertiary and younger volcanics are largely confined to the high plateau forming the backbone of the Isthmus. Pleistocene volcanoes are aligned on the inland edge of the Pacific plain parallel to the coast. The lack of any evidence on the Pacific side of Guatemala of valleys of such size that they would not be concealed by late Tertiary and more recent volcanics, the absence of a coastal plain showing uplift, and the remarkable alignment of the volcanoes point to a possible fracture zone on the western side of which a portion of the Pacific Cordillera has subsided. Along one of the principal lines of subsidence at the intersection of cross-fractures the volcanoes have been built.[1] Uniformly great depths in the

[1] The fracturing is similar to, but more complicated than, that in the Hawaiian Islands (S. Powers, "Tectonic Lines in the Hawaiian Islands," *Bull. Geol. Soc. Amer.*, XXVIII (1917), 501–14).

Pacific Ocean at no great distance from shore and the parallelism to the coast line of the submarine contours are not unfavorable to the theory of subsidence.

Diastrophic movements of considerable magnitude have taken place in Central America at three different periods: at or before the close of the pre-Cambrian, at the close of the Paleozoic, and during the late Miocene. A later movement may be dated as late Pliocene or Pleistocene. The Cordilleran axes were developed during the folding at the close of the Paleozoic, the folding being most intense toward the south. Miocene movements, though less intense, developed parallel Cordilleran trends of the Caribbean system and initiated the cycle of erosion in which the greater part of the dissection of the present mountains was accomplished. Vulcanism undoubtedly began in the present central portion of the Isthmus before the Miocene deformation, as the earlier volcanics are steeply folded. Pliocene and Pleistocene (?) sediments from Yucatan southward through Honduras show evidence of both vertical and tangential movements, tangential movements being especially notable in the youngest sediments of the Atlantic Coast region near Puerto Cortez and Omoa, Honduras, and Lake Izabal, Guatemala.

NOTES ON A COLLECTION OF ROCKS FROM HONDURAS, CENTRAL AMERICA

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Introduction.—The rocks described in this paper were collected by Dr. Sidney Powers during the summer of 1917 from the province of Atlantida, northwestern Honduras, and from the outlying island of Utilla. A summary of the general geology of the region is given in the paper preceding this by Doctor Powers. A high range of mountains composed of batholithic intrusions of granodiorites, the Sierra de Pija, extends along the northern border of Honduras and sends radiating spurs toward the coast. Most of the rocks were collected from stream valleys cutting the northern slopes of these mountains.

The chief centers from which collections were made are Tela, Puerto Cortez, San Pedro Sula, La Ceiba, and Nueva Armenia. These towns are shown in Fig. 2 of the preceding article. The island of Utilla lies 20 miles off the coast and is one of the Bay Islands.

Rocks from Utilla Island.—Utilla is largely fashioned from Quaternary basalts. The basalt which occurs back of the town of Utilla is gray black in color, some of it dense, some of it vesicular. In certain varieties the feldspars abound; in others augite and olivine phenocrysts are more abundant. The groundmass has an ophitic texture and is composed of andesine, augite, and olivine. The feldspar phenocrysts are zoned and have the composition of basic andesine and medium labradorite. Basalts from Stuert Hill, which is probably the center from which the flows came, are similar to the type just described, but are more vesicular and impregnated by calcite. Stuert Hill is composed principally of agglomerate.

Pumpkin Hill, $1\frac{1}{2}$ miles southwest of the town Utilla, is underlain by tuff composed of coarse bits of lapilli and angular fragments

of coral limestone set in a paste of yellowish white ash. The vesicles of basalt are filled with opal, showing that the rock has been thoroughly leached since its deposition on a tuff cone in relatively shallow water.

Rocks from the Tela district.—Near the town of Tela there are a large variety of igneous and metamorphic rocks which are more or less intimately connected by transitional facies. The igneous types vary from granodiorites to gabbros. At the western end of the native village the hills are composed of medium- to fine-grained augite diorites cut by occasional quartz veins. The diorites are composed of basic oligoclase feldspar, biotite, diallage, and accessory apatite and magnetite. Three miles west of Tela, Triunfo Point is formed by a hill of true diorite which varies greatly in size of grain within a few feet. The diorite is black and white in color and consists of acid labradorite, common hornblende (pleochroic olive green to yellow), and accessory magnetite. Similar diorites are exposed in a cut along the Tela Railroad 7 miles west of Tela, and in the headland Bishop Point, 5 miles west of Triunfo Point, the last rocky point for 70 miles to the west. South of Tela, toward the mountains which are locally called the Shark Mountains, felsodacites outcrop in Tela valley associated with dioritic gabbros. The felsodacite is dirty buff in color and contains small phenocrysts of quartz and larger phenocrysts (3 to 8 mm.) of feldspar. The microscope shows that in the recrystallized mosaic of quartz and feldspar myrmikitic intergrowths are common.

A large number of rocks were collected in the Quemada Hills on the west side of Micos Lagoon and about 12 miles east of Tela. The accompanying sketch map (Fig. 1) shows the principal points visited. Typical diorites, such as compose Triunfo Point, outcrop on Mũnos Hill. Philipe Hill is composed of a sheared granodiorite, light gray in color. Under the microscope the rock shows a mosaic texture. Quartz and orthoclase with oligoclase are the chief minerals, but minute flecks of hornblende are abundant and titanite and apatite are present. Apparently intrusive into the granodiorite, since it is less sheared, is a basic diorite composed of labradorite ($Ab_{40}An_{60}$) and a hornblende which is pleochroic, bluish green to light yellow. Apatite and pyrite are also present.

Diorites outcrop on Leandro Hill, and coarse-grained types with large hornblende crystals occur in the valley southwest of this hill. Medium-grained gabbros rich in labradorite, which gives them a greasy, brown appearance, are found on Frijole Hill.

Along Cow Creek and the adjacent creek on the west, Leandro, a series of metamorphic rocks largely derived from tonalites or diorites is found. Pegmatitic facies of the tonalite composed of quartz, orthoclase, and black tourmaline are common in the valley

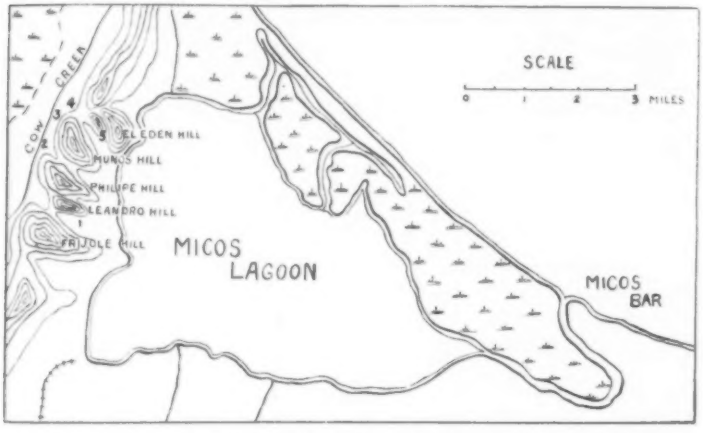

FIG. 1.—Map of vicinity of Micos Lagoon, Northwest of Tela, Honduras

near locality (1) (Fig. 1). At locality (2) a dioritic orthogneiss outcrops. The rock is dark gray in color and is composed of sheared oligoclase feldspar in parallel bands with quartz veinlets. Parallel fine needles of hornblende add to the banded effect and bend about occasional phenocrysts of feldspar. An epidote orthogneiss occurs near locality (3). It is composed of epidote, hornblende, and labradorite and is banded gray and black in color. A greasy mica schist outcrops at locality (4). The paper-thin, crenulated bands of muscovite bend about brecciated crystals of oligoclase which appear as small "augen" inclusions on the cross-fractured rock.

On El Eden Hill, locality (5), hornblendite outcrops north of a ridge of quartzite which is tilted on end. The hornblendites were

undoubtedly derived from the metamorphism of diorites. They are composed of andesine and a hornblende which is pleochroic light yellow and olive green to bluish green. Associated with the hornblendites are dioritic biotite orthogneisses.

Along the Tela Railroad 14 and 16 miles east of Tela sedimentary quartzites and gneisses are exposed, while at Uraca, 56 miles southeast of Tela by rail, medium- to coarse-grained tonalites composed of quartz, oligoclase, and a little hornblende outcrop over a large area. The tonalites extend eastward past San Pedro Sula.

Rocks from Puerto Cortez and vicinity.—The region about Puerto Cortez has been built by shoreward currents and by the vegetation in swamps. But across the bay the waves have exposed a series of Tertiary sandstones which are greenish gray when fresh, but which oxidize to a limonitic clay. They are composed of very fine grains of quartz and muscovite mingled with an equal proportion of glauconite particles. The rock is gritty and friable and hence is quite like a typical green sand both in color and texture.

Proceeding southward along the Honduras National Railroad from Puerto Cortez volcanic rocks similar to those on the island of Utilla overlie sheared felsodacites at Chameleconcito. The particular specimen collected is a dense porphyritic basalt composed of large phenocrysts of labradorite, olivine, and augite set in a cryptocrystalline groundmass of the same minerals associated with magnetite dust.

At Baracoa specimens of an even, fine-grained, dioritic gneiss were found associated with an actinolite gneiss composed entirely of actinolite in rosettes of radiating fibers. Near La Pimienta there are chocolate-colored felsites which show a flow structure and carry small phenocrysts of oligoclase feldspar. When decomposed they form a residual clay very free from iron compounds. They have not been sheared or folded like the other felsites described because they are much younger—probably post-Cretaceous.

Rocks from Landslide Valley, San Pedro Sula.—On account of residual soils fresh rocks are seldom found in Honduras. An exception to this rule occurs, however, in the valley southeast of San Pedro Sula conspicuous for the large bare face of a mountain left by a landslide. Here bronze-colored biotite schists are

associated with diorites. The schist is composed of paper-thin layers of biotite bending around augen crystals of oligoclase and is similar to the schist occurring west of Micos Lagoon, near Tela, save that the mica is predominatingly biotite instead of muscovite. The microscope reveals a granular paste of fine quartz with rosettes of muscovite and parallel plates of chestnut-brown biotite. The diorite is a medium- to coarse-grained variety whose relation to the schist is unknown. Occasionally the diorite is sheared and epidotized.

Rocks from La Ceiba and vicinity.—Among the streams extending from the coast into the hills southeast of La Ceiba, the nearest is Rio Danto. A number of river pebbles were collected from its bed and one specimen was collected from an outcrop in the stream. The pebbles came from the higher interior hills near the headwaters of the coastal streams and were largely tonalites or allied types. The residual bowlders show that the region about La Ceiba is underlain by agglomerates and flows of acid rocks which toward the east around Tela are transformed into gneisses and schists by dynamic metamorphism. A tuffaceous agglomerate containing pebbles of felsodacite is much epidotized, but the microscope shows phenocrysts of oligoclase-albite replaced in part by a mosaic groundmass of small quartz particles. A trachyandesite from the same locality, outcropping in the river, is light yellow to buff in color and shows a slight flow structure. The thin section shows phenocrysts of oligoclase-albite which are not distinct in the hand specimen. The groundmass is composed of a fine mosaic of feldspar and quartz and occasionally there are nests of feldspar in trachytic arrangement.

From the hills north of Rubber Grove, a station on Vaccaro Brothers Railroad, 5 miles southeast of La Ceiba, aporhyolites and rhyolitic agglomerates were obtained. The agglomerates are composed of red pebbles of aporhyolite and jasper bound together by a red quartzose cement.

The Congrejal River flows into the ocean past the town of La Ceiba. Along its lower course acid flow rocks are exposed, but farther south among the mountains it cuts tonalites and gran-

odiorites. Near the town a rounded hill is composed of felsodacite intruded by diorite. The diorite is a medium- to coarse-grained type consisting of hornblende and oligoclase. The hornblende is pleochroic, chestnut brown to light yellow. The oligoclase is occasionally replaced along the albite twinning planes by magnetite. Tonalite porphyries containing phenocrysts of quartz and oligoclase in a glassy groundmass are frequently exposed, as are also agglomerates containing pebbles of the porphyries.

A biotitic tonalite collected 8 miles up the Congrejal valley at an elevation of about 300 feet is pure white in color and coarsely crystalline. It consists of predominating oligoclase feldspar and quartz with occasional flakes and bunches of biotite a centimeter in diameter. A granodiorite which consists of oligoclase-albite, microcline, quartz, and hornblende was collected near the same locality. The rock has been subjected to great strain and the cracks are filled by a mass of small quartz crystals. The tonalite is seen in the field to be cut by the granodiorite, but the contact shows very little chilling of the latter rock. A dark-greenish porphyry cutting the granodiorite and a breccia composed of fragments of granodiorite in a granular matrix, but of uncertain relationship to the other rocks, are seen south of large exposures of the granodiorite in the river bed. North of these exposures, about 5 miles up the valley, quartz veins are very abundant, cutting a rock which looks like a hydromica schist, but which is probably a metamorphosed igneous rock.

Near the mouth of the Masica valley, 25 miles southeast of La Ceiba, there are found tonalites and allied rocks similar to those exposed in the Congrejal valley, but here associated with basic types. An olivine diabase was collected which is composed of labradorite, augite, olivine, biotite, a little brown hornblende, and pyrite. A coarse-grained black wehrlite was also found consisting of olivine and augite in about equal proportions and a very small amount of labradorite. The olivine crystals often include rounded and resorbed bits of augite.

At San Francisco, 15 miles southeast of La Ceiba, basalt porphyry bowlders with labradorite phenocrysts 2 to 3 cm. in

diameter were picked up in the stream bed. A granodiorite collected from this vicinity has approximately the following composition:

	Percentage		Percentage
Oligoclase	50	Biotite	4
Orthoclase	20	Hornblende	1
Quartz	25		
			100

Rocks from the vicinity of Nueva Armenia.—Hot springs in the hills 5 miles south of Nueva Armenia and 1½ miles east of the Tropical Timber Company's railroad well up through tonalites and have kaolinized these rocks extensively. The fresh tonalite is a light-gray rock consisting of oligoclase, quartz, and hornblende. Gneissic varieties of the tonalite are found associated with coarse-grained diorites composed of oligoclase and hornblende. One specimen of the diorite shows a small amount of biotite.

Summary.—The igneous and metamorphic rocks collected from the province of Atlantida, Honduras, include the following types:

- Granular rocks
  - Granodiorite
  - Tonalite
    - Biotite tonalite
    - Pegmatite tonalite
  - Diorite
    - Augite diorite
  - Gabbro
    - Dioritic gabbro
  - Wehrlite
- Cryptocrystalline and glassy rocks
  - Aporhyolite
  - Felsite and agglomerate
  - Tonalite porphyry
  - Felsodacite and agglomerate
  - Trachyandesite
  - Olivine basalt, agglomerate, and tuff
- Metamorphic rocks
  - Dioritic orthogneiss
  - Epidote orthogneiss
  - Actinolite gneiss
  - Hornblendite
  - Biotite schist
  - Quartzite

The granular types occur largely near the summits and on the north slope of the mountains forming the Sierra de Pija, while the extrusive types are found near the coast. The geologic events in the history of the region as revealed by the rocks studied may be epitomized as follows:

1. Intrusion of granodiorites and tonalites accompanied by the extrusion of allied rock types.
2. Folding.
3. Intrusion of diabases and diorites.
4. Faulting and crushing.
5. Extrusion of olivine basalts.

LOESS-DEPOSITING WINDS IN LOUISIANA

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The data on which this paper is based were accumulated from field work on the two loess belts of Louisiana together with a few examinations of loess at Vicksburg and Natchez, Mississippi. Practically all the evidence points to an eolian origin for the southern loess. Assuming this origin, it appears from two lines of evidence, namely the amounts and thickness and the chemical composition of this loess, that the principal depositing winds were westerly and southerly.

THE LOESS

The loess in Louisiana is of brownish to gray-brown colors and shows the usual vertical cleavage. For the most part it overlies Lafayette and Columbia sandy and gravelly materials and Pleistocene clays which are usually correlated as Port Hudson. It was deposited on an eroded surface, hilly in most places where the loess overlies the Lafayette and Columbia formations, and rolling to undulating where it overlies the clays (Fig. 1). There are two loess belts fringing the Mississippi lowlands, extending nearly to the Gulf. The eastern belt, beginning about 15 miles south of Baton Rouge, about 80 miles from the Gulf, with a width of about 15 miles, widens to the northward to a width of perhaps 40 miles in Mississippi. This belt continues northward through Tennessee to the Ohio River with practically no interruptions except at stream valleys. The western belt begins near Lafayette about 40 miles from the Gulf and extends to the Red River valley, a distance of about 50 miles, with an average width of 8 to 10 miles. Ten miles to the north the loess again appears in an island-like area, the Avoyelles Prairie, of about 80 square miles. About 40 miles northeast the loess belt again reappears at Sicily Island, from which it extends northward into Arkansas in a belt known locally as the

Bayou Macon Hills, with a width varying from 5 to 15 miles. The western loess belt is seen to be somewhat longer but much narrower than the eastern belt.

These belts in Louisiana show contrasts in thickness and in the outlines of their margins away from the Mississippi. The eastern belt, beginning with a thickness of from 10 to 12 feet, thickens to

FIG. 1.—Loess overlying a buried hill of red Lafayette materials. The arrows point to the contact. West Feliciana Parish, Louisiana.

the northward to about 15 to 20 feet at Bayou Sara, 35 miles to the northward; at Vicksburg it is from 30 to 40 feet thick. The western belt, with about the same thickness at the south, thickens but little to the north, being but 12 to 15 feet thick in the Bayou Macon Hills, nearly 200 miles to the north. The eastern belt in Louisiana ends rather abruptly at the Amite River. On the west side of this stream the observed thickness is about 6 feet, while across the valley two miles to the eastward the loess is much thinner and sparsely developed. On the other hand, the western belt thins so gradually that its western limits can only rarely be observed. The

two belts correspond in having the thickest loess near the Mississippi lowlands.

Here, as in most places elsewhere, the loess shows the characteristic uniformity in size of particles. There are no available mechanical analyses of the lower part of the loess, but several analyses of lower subsoils show that about 70 per cent ranges in size from $\frac{5}{100}$ to $\frac{1}{100}$ mm. in diameter and about 20 per cent is below this diameter. The remainder is composed of particles but slightly larger than $\frac{5}{100}$ mm. in diameter. In general the loess particles of Louisiana seem to be more rounded than those farther north, so far as the writer can judge from the examination of half a dozen samples from Iowa and Illinois. This difference is doubtless to be explained by the fact that the southern loess particles have been subjected to long transportation by the Mississippi. In the main body of the loess an examination of perhaps 500 exposures shows little if any stratification, although here and there there are faint indications of such structure. For example, the snail shells which are abundant locally show in a few places a rude horizontal alignment and lie in thin dark streaks suggesting buried soils. In a few places dark bands never more than a few inches long and probably due to iron and manganese coatings suggest that these substances have accumulated along bedding planes. A sharp contact between the loess and the underlying materials has never been observed, but rather there is a transition zone 3 to 20 inches in thickness. The transition is most indefinite between the loess and underlying clays, for there is more or less similarity in texture and in some cases in color. Where Lafayette and Columbia sandy materials underlie the loess, there is in places a "feathering" of the one into the other and in places very faint stratification.

THE ORIGIN

Two problems are involved, (1) the source of the loess materials, a problem with which this paper does not deal directly, and (2) the secondary or the depositing agents. Since the loess belts follow only the Mississippi lowlands and do not extend up the tributaries, it is clear that there is a genetic relation between the river from Cairo southward and the loess. The Mississippi doubtless carried

the loess materials, and the agent of final loess placement on the uplands adjoining the river narrows either to water deposition or to winds carrying materials from the lowland.

The explanation of southern loess as wind-blown dust not only presents the fewest difficulties but is distinctly supported by most of the loess features. The smallness of grains can be explained by the weakness of wind transportation, for, according to the experiments of Udden, only dust particles with diameters of .18 mm. and less are readily borne by ordinary winds.[1] We have noted that about 70 per cent of the loess is composed of silt particles from .05 to .01 mm. in diameter and that the mechanical composition is notably uniform. The practical absence of coarse particles is, of course, explained by the inability of ordinary winds to carry them. Udden thus explains the small percentages of very fine particles.[2]

The writer suggests another reason for the relatively small percentages of very fine materials (clays) in the loess. Observations on clay and silt plowed fields in Kansas during dry seasons showed that more dust blows from the coarser silt soils than from the clay soils. The reason apparently is that, during a dry season, the clays bake more than the silts and so offer more resistance to the winds. According to this conclusion, if the Mississippi upon subsiding left areas covered here with silt and there with clay, the winds would carry a larger proportion of silt than of clay.

In a large river like the Mississippi it would seem impossible for the water to deposit its sediment with practically no stratification, even if the water carried only loessial materials, for the loess contains from 5 to 10 per cent of fine sand, and in places this coarser material would be segregated. The loess materials carried by the Mississippi were in large part carried from drift regions to the northward and, even granted that the drift furnished only fine materials, the streams south of the glaciated region, such as the Arkansas, Yazoo, and Red rivers, were doubtless contributing their sandy loads, so that the Mississippi could not have carried only a loessial

[1] *Journal of Geology*, II (1894), 323.

[2] "The finest materials carried by the air are not deposited in so great a proportion with the coarse materials as they would be if the atmosphere carried a greater load. The finest materials settle only in extreme calms" (*ibid.*).

load to the Louisiana region. Furthermore, such a river in flood would necessarily back up the tributaries and loessial materials would be deposited along the tributaries in contrast with the actual fairly straight margin where it crosses a tributary.

So far as the structure of the loess is concerned, it might have accumulated in lakes or have been deposited by winds, but in the hundreds of miles of loess belts below Cairo there are no restraining barriers which would impound lakes. Moreover, lakes in which 10 to 50 feet of loess accumulated must have existed long enough for deltas to have been built and shore lines developed, for in such temporary lakes as the Red River raft lakes of Louisiana one may find well-developed shore lines around these nearly drained lakes. No such shore lines have been seen in the Louisiana loess areas and none to the writer's knowledge have been reported elsewhere in the Lower Mississippi Basin.

The relations of the loess to the underlying buried Lafayette-Columbia sandy hills near the Mississippi strongly suggest an eolian origin (Fig. 1). The absence of truncation of these buried hilltops, the very faint or frequent absence of interstratification of loess and sand at the contact, all point to a weak depositing agent such as wind. The greater thickness of loess near the Mississippi is not inconsistent with an eolian origin, for the dust-laden winds blowing from the lowlands to the uplands would have their velocity checked and so drop part of their load near the river. The work of Shimek shows that the loess fossils in this region, mostly snails, belong to a land fauna, there being "no species which are aquatic or even semi-aquatic,"[1] and the virtual absence of a water fauna is equally significant.

DIRECTIONS OF LOESS-BEARING WINDS

Assuming the eolian theory of loess in Louisiana, there are three lines of evidence available as to the directions of loess-depositing winds, namely: (1) the width and thickness of the loess belts on either side of the Mississippi, (2) the composition of the loess, and (3) the thickness of loess on some isolated areas which were exposed to the sweep of winds from many directions.

[1] *Am. Geologist*, XXX, 282.

1. The greater thickness and width of the eastern loess belt have been noted by many observers and usually explained as due to stronger and perhaps more persistent westerly depositing winds. From a rough calculation based on field notes the writer estimates that the loess in Louisiana below the Mississippi state line includes about 4 cubic miles, while the corresponding portions of the western belt includes only .8 of a cubic mile, or, roughly estimating, there is about five times as much loess in the lower eastern belt as in the corresponding portions of the lower western belt. These contrasts point to the greater work of westerly as compared with easterly winds.

2. The same conclusion seems to be indicated by the composition of loessial soils in the two belts. While the analyses are of soils and subsoils only, it is believed that the *range* of their compositions corresponds to that of the underlying loess, since the soils have been subjected to practically the same weathering processes over both belts. Taking the composite soil analyses of the eastern loess belt below the Mississippi state line and the corresponding portions of the western belt, we have the following data:[1]

	Number of Analyses	Lime (Lbs. per Acre)	Potash (Lbs. per Acre)	Phosphoric Acid (Lbs. per Acre)
Eastern belt	21	5,540	8,500	980
Western belt	14	6,000	8,920	1,800

The lime and potash are slightly higher in the western belt, and the phosphoric acid decidedly so. So far as can be determined by a microscopic examination, the lime and potash occur in feldspars with diameters mostly $\frac{1}{100}$ mm. in diameter or less. Most of the phosphoric acid occurs in the very fine particles, the fine silts and clays, with diameters below $\frac{5}{1000}$ mm. These fine particles are difficult to study microscopically, and the writer has been unable to identify the phosphate-carrying minerals except for an occasional particle of apatite. However, the point to be emphasized in this connection is that the particles carrying lime, potash, and phosphoric acid are very small, and it is believed that the higher

[1] Analyses by I. Selecter, Soil Chemist, Louisiana State Agricultural Experiment Station.

percentages of these minerals in the western belt are due to a differential selection of wind load. The weaker easterly winds carried a relatively finer load than the stronger westerly winds, with the result that higher percentages of lime, potash, and phosphoric-acid-carrying minerals were deposited in the western loess belt.

3. The third line of evidence concerns the effectiveness of northerly winds as compared with southerly winds as loess-carrying agents. The Avoyelles Prairie (see Fig. 2) is an island-like area of

FIG. 2.—Map showing the loess belts (dotted) in Louisiana and Mississippi. (Loess in Mississippi after Mississippi Geological Survey.)

about 80 square miles, which is entirely surrounded by alluvium and capped by a layer of loess overlying Lafayette-Columbia and Port Hudson materials. The platform on which the loess rests is 10 to 15 feet above the alluvium in the two places where the top of the platform was observed. This relatively elevated area was exposed to the sweep of the winds from all directions, with no loessial soil within 10 to 30 miles, and it seems clear that the prevalent winds would deposit the thickest loess in a manner analogous to the drifting of snow in some regions. The loess-bearing winds from the south, for instance, would drop a portion of their load on

reaching the low elevation. If the elevation were of small area, there might also be an accumulation of dust on the lee side of the obstruction, as snow drifts on the lee side of a tight fence; but in this case the winds passed over several miles of low upland, and it seems probable that most of the heavy load would be deposited on the windward side and but little dust would be left to accumulate on the leeward side. The loess on the Avoyelles Prairie is about 12 feet thick at the southern end of the area and 6 to 7 feet thick at the northern end, a difference in thickness indicating southerly rather than northerly winds as the main depositing agents. No sections were observed which allow comparisons of thickness on the eastern and the western sides. About 40 miles east of north from the Avoyelles Prairie is Sicily Island, the southern extremity of the Bayou Macon Hills, which, as we have seen, is a loess-covered ridge extending from Arkansas into Louisiana. At the southern end of Sicily Island the loess is from 12 to 14 feet thick, and about 7 miles northward it thins to 7 to 10 feet. The evidence here is not so clear, for the dust may have accumulated on the lee side of the ridge from northerly winds, or it may have accumulated from the deposition by southerly winds at the southern side of Sicily Island. However, it seems that the thicker loess at the southern ends of both these elevations points to the greater effectiveness of southerly winds as loess-depositing agents as compared with northerly winds.

PRESENT WINDS

There is some interest in comparing modern wind directions to ascertain, if possible, whether the most effective modern winds in this region are at present westerly and southerly. Unfortunately no positive conclusions can be reached, because one cannot be sure that the average for so short a time as that for which we have records represents the modern wind directions, and, furthermore, the important elements of wind persistence and velocity are not given in the reports. Fig. 3 shows the average prevailing wind directions for the several months at New Orleans, Louisiana; Vicksburg, Mississippi; and Memphis, Tennessee, for periods of thirty-six, thirty-five, and thirty-five years respectively. The winds at Vicksburg and Memphis are more significant than those at New

Orleans, for Vicksburg and Memphis are located on the loess, and, moreover, the directions at New Orleans are complicated by local land and sea breezes which do not extend far inland. It will be seen that the prevailing winds at New Orleans and Vicksburg are

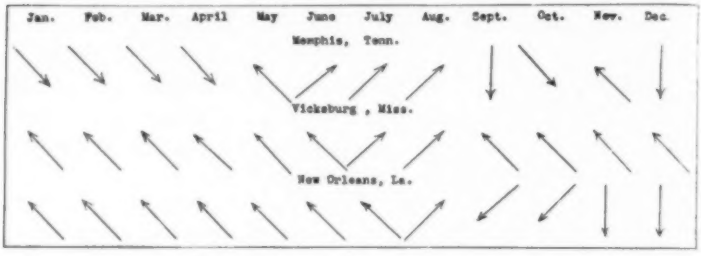

FIG. 3.—Diagram showing the directions of prevailing winds at New Orleans, Louisiana, Vicksburg, Mississippi, and Memphis, Tennessee. (Data from *Bulletin Q*, by A. J. Henry, U.S. Weather Bureau, 1906.)

southerly, and probably would account for the greater accumulation of loess at the southern ends of Avoyelles Prairie and Sicily Island. On the other hand the easterly winds greatly exceed those from westerly directions, except at Memphis, where the westerly

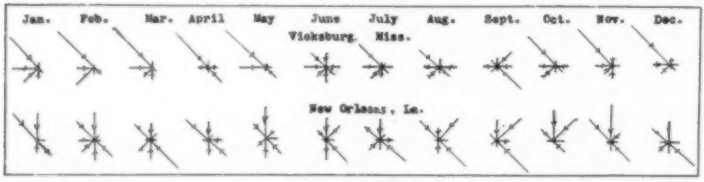

FIG. 4.—Diagram showing the occurrences of high winds at New Orleans, Louisiana, and Vicksburg, Mississippi. Lengths of arrows are proportional to frequency. (After data by I. M. Cline, of the U.S. Weather Bureau at New Orleans, and W. E. Barron, of the U.S. Weather Bureau at Vicksburg.)

winds predominate. Fig. 4 shows the frequency of high winds at New Orleans and Vicksburg. At New Orleans about 26 per cent of high winds are from easterly directions, 17 per cent from westerly directions, 32 per cent from northerly directions, and 25 per cent from southerly directions. At Vicksburg 29 per cent of high winds

are from northerly directions, 16 per cent from southerly directions, 11 per cent from easterly directions, and 43 per cent from westerly directions. It should be noted that only the highest winds are included in the data given above. Undoubtedly the high winds are effective dust carriers, but loess is so fine grained that it could doubtless be carried by ordinary winds, other things being favorable. Fig. 3, which shows the winds of all velocities, probably is more significant than Fig. 4, which shows only a part of the high winds. Remembering the much greater thickness and width of the eastern loess belt, it would seem that the present winds would not be competent to account for the disparity between the eastern and western loess belts. This is certainly true so far as occurrences are concerned, and there is no reason to believe that either the persistence or velocity of winds from any one direction are especially notable. During loess-depositing times westerly winds must have been more predominant than at present. The present southerly winds would seem to be competent to deposit the greater thickness of loess at Avoyelles Prairie and Sicily Island. Obviously more observations of loess thickness on isolated areas are needed before positive conclusions can be drawn as to the efficiency of southerly winds.

SUMMARY

(1) The greater efficiency of westerly winds in the southern loess belts is shown by (*a*) the greater width and thickness of the eastern loess belt and (*b*) by the higher percentages of lime, potash, and phosphoric acid of the soils of the western belt. (2) The greater thickness of loess on the southern sides of two isolated loess areas indicates that southerly winds were more efficient in this region than northerly winds. (3) From the meager data available it would seem that westerly winds were more frequent and effectual in loess-depositing times than at present.

VOLUME CHANGES IN METAMORPHISM

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Introduction.—It is the purpose of this paper to consider volume changes of rocks in relation to metamorphism. This is a subject which has already received much attention by geologists and physical chemists, but it seems to me that the former have not always appreciated the true conditions of metasomatism, while the latter have limited themselves largely to the consideration of transformations in systems in open space. The changes in the rigid rocks are subject to certain limitations to which I believe sufficient attention has not been directed.

Known changes of volume.—It is evident and well known that volume changes in rocks take place. The most efficient agencies are molecular forces: heating and cooling, fusion and solidification, molecular rearrangement (as when a mineral passes any inversion point). All of these may affect the volume of large or small masses of rocks. Injection of igneous material may increase the volume. Stretching of a geological body may result in cracks and fissures, increasing the bulk volume, and if these are filled by circulating solutions the actual volume will be greater than before. In the same way processes of filling may increase the actual volume of a porous rock. It is also well known that diminution of volume may take place in unconsolidated sediments under pressure, by closing of pores or other openings, and by incidental squeezing out of any fluid or gaseous phase which the rock may contain. In such rocks lateral movements of plastic material may occur, though this would only effect a relative change of volume. Similar relative volume changes occur by recrystallization under conditions of rock flowage (as in case of marble or ice).

Close to the surface where disintegrating agencies are at work volume changes may take place. The pressure is slight and chem-

ical reactions proceed accompanied by increase or decrease of volume. Here hydration will result in expansion and strong solvent action may be followed by contraction of volume.

Metamorphism and metasomatism.—Metamorphism is here defined as the sum total of the chemical and mechanical changes which take place in solid rocks, below the zone of oxidation. The agents are heat, pressure, and chemical energy. Metamorphism by pressure is probably always accompanied by some chemical change. Chemical energy works by means of solutions, gaseous or liquid, which penetrate the rocks on capillary and supercapillary openings.

Metasomatism is here defined broadly as any change in composition of a mineral when exposed to conditions under which it is unstable. Solutions, gaseous or liquid, effect the change. A more restricted definition is that metasomatism comprises any change in composition of a mineral in a solid rock induced by a change in the physical conditions and resulting in its space being occupied by another mineral stable under the prevailing conditions.

Metamorphism is in most cases accompanied by metasomatism of individual minerals and usually also by metasomatism of the rock as a whole, though the latter change may proceed very slowly. If the supply of new material is rapid the composition of the rock may be greatly changed within a short time. Replacement is used as equivalent to metasomatism.

Thesis of this paper.—In a previous paper,[1] principally devoted to metasomatism in mineral deposits, I have advanced the view that replacement normally occurs without change of volume of individual minerals or rocks. I would now like to broaden this theory by the thesis that metamorphism by replacement does not normally involve changes of volume.

Replacement.—Replacement in solid rocks consists in solution of the host mineral, followed immediately by deposition of an equal volume of the guest mineral. This is an empirical observation based on the microscopic examination of rocks. In other words the volume of the replacing mineral equals the volume of the mineral replaced. Deposition follows so closely upon solution that at no

[1] "The Nature of Replacement," *Econ. Geology*, VII (1912), 521–35.

time can any open spaces be discerned under the microscope. It is evident, however, that capillary spaces are necessary for the movement of the fluid phases which in most cases are aqueous solutions. In fact, replacement usually begins from such capillary cracks or from a series of minute fluid inclusions along such a fissure. Replacement is primarily caused by solution or decomposition of the host mineral in solute films separating grains and filling capillary fissures. The solution of the host mineral produces supersaturation in the liquid, and an amount of secondary material is precipitated equal to the volume of the host mineral removed.

Replacement proceeds particle by particle but not "molecule for molecule." In other words there is no simple molecular equivalence between the material dissolved and the material precipitated. Replacement proceeds independently of specific gravity and molecular volume. Chemical reactions may take place in the contact film, but the sum total of the change is not expressible by the chemical formulas usually supposed to represent the process.

In some cases there is simply solution and deposition without chemical reaction, as when pyrite replaces calcite or limestone or shale, but whether or not the exchange is accompanied by chemical reaction does not influence the law of equal volumes. Replacement is dependent upon the velocity of the solution movement and naturally also upon composition, pressure, and temperature of the replacing solution. If the speed and chemical activity of the solutions be great the empirical volume law may fail to hold, deposition will lag behind solution, and a drusy texture will result. This happens occasionally in some metasomatic processes in the formation of mineral deposits, but in metamorphism of rocks the solutions move slowly and only a small amount of new material is introduced, so that the resulting textures are always compact. Even in the case of drusy texture the bulk volume remains the same and subsequent rock pressure fails to close the cavities, even under the weight of a rock column of 10,000 to 15,000 feet. Ultimately, at extreme depths these cavities would most probably be closed with permanent reduction of volume if they have not previously been filled by cementing solutions.

While, therefore, in extreme cases of metasomatism there may be diminution of actual volume expressed in porosity, the opposite, i.e., increase in volume, it is believed, will not take place by replacement in rigid rocks.

Form and texture of guest mineral.—The guest mineral may form aggregates with their irregular outlines simply determined by the ways open for the replacing solutions. In this case, as in replacement of feldspar by sericite, there are capillary openings between the individuals of sericite, and the space is thus filled less continuously than in the host mineral. In other words the porosity may increase by several per cent. The altered rock is then more accessible to later solutions and may easily suffer further alteration if the solutions change so as to make the new mineral unstable.

In other cases the guest mineral is compact and may assume its own crystal form, owing, it is believed, to differential pressure and corresponding difference in rapidity of growth in certain directions. At times the replacement may proceed so rapidly that parts of the host mineral or host minerals become inclosed by the guest mineral, as frequently seen in quartz crystals in limestone or garnets and ottrelites in crystalline schists.

Movement of solutions on capillary fissures.—I am aware that attempts have been made to show that circulation of solutions on capillary fissures is so slow as to be negligible.[1] While not able to refute these calculations, I can only say that the whole process of metamorphism appears to be opposed to such a conclusion.

Metasomatic shells.—It is frequently observed that metasomatic crystals, for instance, cubes of pyrite in feldspar, are surrounded by a thin covering of another mineral, i.e., quartz or chlorite following the outlines of the crystal. This is believed to mean that at a certain stage the iron solutions failed. The replacement proceeded, but instead of pyrite the next combinations available in the replacing solutions were precipitated.

Complex replacement.—One guest mineral may replace two or several host minerals without change of its crystallographic form. One pyrite crystal may extend across the contact of a quartz and a

[1] J. Johnston and L. A. Adams, *Centralblatt für Mineralogie*, 1914, p. 171.

feldspar grain. In schists one garnet crystal may replace hundreds of small individuals of biotite, quartz, and feldspar.

Examples of replacement.—The following instances are mentioned, in order to express more precisely what processes are believed to be active in certain cases.

In the simple case when pyrite replaces calcite the solutions need to carry iron sulphide, alkaline sulphides, and carbon dioxide. As each particle of calcite is dissolved as bicarbonate, the solution becomes supersaturated for FeS_2 and an equal volume of this compound is precipitated.

In the more complicated case of replacement of orthoclase by pyrite the entering solution would have the same composition as indicated above. As each particle of orthoclase is decomposed into potassium carbonate, colloid silica, and colloid aluminum silicate, all of which are carried away, a corresponding volume of FeS_2 is deposited.

When pyrite replaces chlorite the entering solution may contain only hydrogen sulphide, iron carbonate, and carbon dioxide. As each particle of chlorite is decomposed into magnesium bicarbonate, ferrous bicarbonate, colloid silica, and colloid aluminum silicate, a reaction takes place between the ferrous carbonate and the hydrogen sulphide, resulting in the precipitation of an equal volume of iron sulphide. The guest mineral contains much more iron than the host mineral and the additional amount needed must be supplied by the entering solution.

Every petrographer knows how frequently soda-lime feldspar or anorthite is replaced by calcite. It is usually explained as a simple case of the lime in the feldspar combining with carbon dioxide. A calculation based on respective specific gravities of 2.75 and 2.71 will show that one cubic centimeter of anorthite yields 2.20 grams alumina and silica, which must be carried away. In order that the resulting calcite may fill the space made vacant by the anorthite the solutions must supply an additional amount of 0.97 grams CaO besides the necessary CO_2, considering that one cubic centimeter of calcite contains 1.52 grams CaO and 1.19 grams CO_2.

The conversion of olivine (forsterite) to iron-free serpentine is usually expressed by the formula:

$$2Mg_2SiO_4+2H_2O+CO_2=H_4\ Mg_3Si_2O_9+MgCO_3.$$

Replacement by equal volumes demands that one cubic centimeter of forsterite (Sp.G. 3.21) must be decomposed and its space filled by serpentine (Sp.G. 2.50). The former measure contains 1.83 grams MgO and 1.38 grams SiO_2, while one cubic centimeter of pure serpentine contains 1.08 grams MgO, 1.10 grams SiO_2, and 0.33 grams H_2O. It is therefore necessary that 0.33 grams water should be added and that 0.75 grams MgO and 0.28 grams SiO_2 should be carried away. This indicates that the foregoing formula does not express the process correctly.

The well-known alteration of orthoclase to sericite is usually considered to be governed by one of the following formulas:

$$3KAlSi_3O_8+H_2O+CO_2=K\ HAl_3Si_3O_{12}+K_2CO_3+6SiO_2$$
$$3KAl\ Si_3O_8+H_2O=KHAl_3Si_3O_{12}+K_2SiO_3+5SiO_2$$

One cubic centimeter of orthoclase (Sp.G. 2.60) contains 1.68 grams SiO_2, 0.48 grams Al_2O_3, and 0.44 grams K_2O. One cubic centimeter of sericite holds 1.25 grams SiO_2, 1.06 grams Al_2O_3, 0.33 grams K_2O, and 0.12 grams H_2O. The replacement by equal volume, therefore, demands removal in solution of 0.43 grams SiO_2 and 0.11 grams K_2O, but also an addition of 0.58 grams Al_2O_3 and 0.12 grams H_2O. This indicates that the formulas cited above are certainly incorrect. The exact formula expressive of what has happened is probably very complicated. A crude approximation would be represented by the following equation:

$$3(K_2O\cdot Al_2O_3\cdot 6\ SiO_2)+4H_2O+3\ Al_2O_3+CO_2$$
$$=2(2\ H_2O\cdot K_2O\cdot 3\ Al_2O_3\cdot 6\ SiO_2)+6\ SiO_2+K_2CO_3$$

It is thus seen that sericitization involves a great addition of alumina. From where is this derived? It must be remembered that sericitization is usually accompanied by many other metasomatic processes involving replacement of aluminous silicates by pyrite, calcite, and chlorite. All these processes involve the liberation of much alumina which is ready to enter into the sericite

molecule. The last example also shows that alumina is by no means an immobile constituent during the metamorphic processes.

Preservation of texture and structure.—The best proof that no volume change takes place during metamorphism is furnished by the frequent preservation of texture and structure. We find the sharp outlines of an olivine crystal preserved, though it may be wholly converted into serpentine. We find calcareous oölites metasomatized by fine-grained quartz; silicified dolomites similarly preserve the outlines of their individual crystals. Fossils are preserved in exact outlines after silicification or pyritization. Basic rocks are chloritized with perfect preservation of outlines of ferromagnesian silicates. Zinc carbonate sometimes reproduces faithfully the texture and structure of limestone.

Replacement under uniform pressure.—It will be necessary to consider replacement under uniform pressure separately from the more complicated conditions of stress. Uniform pressure results in increase of solubility, but the effects are slight compared to a relatively small change in temperature.[1] Uniform pressure obtains in static metamorphism, which, for instance, is active in the upper part of the crust, where hydration is an important process and the temperature not high. Rocks penetrated by solutions under static metamorphism develop many minerals by replacement, for instance, sericite, chlorite, calcite, epidote, serpentine, pyrite, etc. In many cases there would be a tendency toward increase of volume because heavier minerals are replaced by hydrated products. It is believed, however, that the law of equal volumes holds strictly in case of this form of metamorphism and that changes of volume have been more frequently assumed to exist than actually proved. Consider an ordinary diabase altered to greenstone. Such a rock is a veritable laboratory of metasomatism: sericite after feldspar, chlorite after augite, epidote, calcite, and quartz after any of the primary minerals. All these replacements are constantly going on in such a rock, and I think that in no case has any change of volume been actually proved. It would not seem impossible to do so, for instance, in case of a thick dike in sedimentary rocks.

[1] J. Johnston and Paul Niggli, "The General Principles Underlying Metamorphic Processes," *Jour. Geol.*, XXI (1913), 504.

The serpentinization of magnesian rocks is often cited as a clear case of expansion by replacement. Recalling the olivine crystals referred to above, I believe it improbable that such an expansion has taken place. Large serpentine masses do not usually show the smooth slickensides supposed to be caused by this movement but are rather compact and solid, the slickensided fragments being confined to crushed zones or near the surface where yielding was possible. It seems much more probable that the replacement has been effected with extensive removal of magnesia, and this is supported by the prevalence of ascending magnesian waters where serpentines abound as in California.

Expansion by hydration of anhydrite I regard in the same light. If it takes place it is under exceptional conditions of light load. Many anhydrites altering to gypsum show no evidence of expansion, the veins of the latter mineral cross-cutting the crystalline structures without disturbance. Some gypsum evidently goes into solution.

Calculation of volume changes.—In view of what has been said above it must be concluded that the application of Lepsius' volume law[1] $\left(\text{Mol. vol.} = \frac{\text{mol. weight}}{\text{Sp.G.}}\right)$ to calculate volume changes in metamorphic rocks formed under uniform pressure is unwarranted and leads to totally erroneous conclusions, unless every detail of the complicated processes is known.

Contact metamorphism under uniform pressure.—In many cases contact metamorphism proceeds under uniform rock pressure. There is, however, strong gas pressure, and if its gradient is high this may appreciably affect the replacement. Contact metamorphism may take place with or without rock metasomatism. In the special case of intense metasomatism of limestone under the influence of extremely hot and concentrated gases one would think that changes of volume would occur if anywhere. And yet the field evidence as well as the microscopical evidence is strongly opposed to such a view as I have shown in the Clifton-Morenci

[1] Van Hise expresses this law as follows: "The volume of the original compound is to the volume of the compound produced directly as their molecular weights and indirectly as their specific gravities" (*U.S. Geol. Survey, Monograph 47*, p. 209).

district; other observers have come to the same conclusion.[1] A great quantity of CaO and CO_2 are carried away, but the volume of the mass remains the same; even drusy textures are rare. Accessions from the magma to form the contact metamorphic silicates have evidently balanced any shrinkage. If there were no accessions from the outside and if the silica and alumina combined with the lime to contact metamorphic silicates, considerable shrinkage would undoubtedly result provided always that opportunity were available for the gas phase to escape. In such a case the volume changes could be calculated by means of the appropriate simple chemical equations and Lepsius' volume law.[2] As a matter of fact such rocks do not show evidence of shrinkage, such as would be afforded by drusy texture, and no field evidence indicating such contraction has been brought forward. I must conclude that here, too, calculations of volume relations on the basis of Lepsius' law applied to the ordinarily used equations are worthless as indicating the actual process. It is believed that eventual tendency to contraction is equalized by additions of substance from circulating waters at the time of metamorphism.

In the case of hornfels derived by contact metamorphism from shales the mineralogical relations have been fully covered by V. M. Goldschmidt and earlier writers, but neither the microscope nor the field examination corroborate an assumption of reduction of volume. As heavy aluminum silicates have been formed it seems that contraction would take place unless counterbalanced by additions. Here also I believe that the replacing solutions, not necessarily of magmatic origin, have carried a certain amount of material into the rock and that when a heavy silicate is formed the remainder of the space will be filled by some other substance, say quartz or feldspar.

Replacement without liquid solutions.—Water solutions certainly circulate in the rocks of the upper metamorphic zones. It would

[1] W. Lindgren, *U.S. Geol. Survey, Prof. Paper 43*, 1905; F. C. Calkins, *ibid., Prof. Paper 78*, 1913, p. 132; B. S. Butler, *ibid., Prof. Paper 80*, 1913, p. 90; J. B. Umpleby, *ibid., Prof. Paper 97*, 1917, p. 71.

[2] Joseph Barrell, *U.S. Geol. Survey, Prof. Paper 57*, 1907, p. 149; also "The Physical Effects of Contact Metamorphism," *Am. Jour. Sci.*, Fourth Series, XIII (1902), 279–96.

be very difficult to account for metasomatism without them. It is considered possible, however, by some investigators that replacement may be effected by gaseous phases, not of magmatic origin, but simply induced by the heat of contact metamorphism in the outer zone. Goldschmidt[1] thinks so. It seems to me, however, that if this be true there would certainly be contraction evidenced in texture and possible to detect by field or microscopic methods.

Metamorphism under stress.—Under unequal pressure, as pointed out by Johnston and Niggli,[2] the solubility will be greatly increased, and its influence on reactions which are accompanied by the evolution of a gas is enormous. "Unequal stress will cause reactions between solids accompanied by the development of a gas phase to proceed to an extent which would be inappreciable in the absence of stress." The conditions in a rock under heavy stress are greatly complicated by the lateral movement of material by flowage (as shown by experiments on marble, ice, etc.). This action has nothing to do with replacement, but it certainly has a tendency to compress and thin the beds. No actual contraction of volume except by the closing of pores is involved in this operation.

Under heavy stress it is commonly assumed that all capillary spaces will be closed and that circulation of water and escape of volatile phases take place with the utmost difficulty. Whether this assumption is correct is not known. It is probably not true in case of limestone, which seems to be easily penetrated by liquids and gases.

Under and after conditions of stress there is often a strong tendency to development, by replacement, of heavy aluminum silicates of small molecular volume, such as staurolite, andalusite, and cyanite. This has generally been interpreted as meaning a reduction in volume, an interpretation which at first glance seems reasonable enough. Most calculations of changes of volume according to Lepsius' volume law are based on such changes.

[1] "The relations [referring to hornfels, etc.] are valid independently of the state of the solvents, whether these are watery solutions or a melt or whether the minerals simply are separated by a space containing their gaseous phases" (*Die Kontactmetamorphose im Kristianiagebiet*, 1911, p. 122).

[2] *Op. cit.*, p. 614.

Niggli, for instance, calculates the contractions of volume of certain ottrelite schists[1] on this basis starting with a shale of assumed composition. The conditions here are very complex, and I am sure that such computations should be undertaken with the greatest caution.

Field geology has never, as far as I am aware, proved that a contraction of volume has taken place except by rock flowage. From the standpoint of microscopic investigations there is no evidence that replacement operates in a manner different from that in rocks under uniform pressure, except that under stress the crystals tend to become elongated in direction of minimum stress. In the phenomena following relaxation of pressure, such as the development of metacrysts of garnet and andalusite, chiastolite and sillimanite, we see all the familiar phases of normal replacement, i.e., crystal form, inclusions of matrix, and complete filling of space. No crystalline schist has a drusy texture or structure indicating contraction cracks. These metacrysts or porphyroblasts develop normally across the matrix[2] and present no indication that the "force of crystallization" has bulged the rock mass, a most improbable hypothesis considering the conditions in the deep zones. Only if we assume that the rocks be actually soft is any such view tenable. It is true that the lamellae of mica sometimes bend around the crystal. These phenomena have been studied by several authors[3] who have concluded that they are caused by later mylonitic movements on gliding planes producing rotation and also development of "quartz tails" on both sides of the crystal. That rotational movements actually have occurred has been proved among others by F. H. Lahee and H. Backlund. Conditions of stress resumed after the compact crystals had been formed by replacement would naturally tend to bend the elastic mica plates around the hard bodies just as glacial clays often form layers conforming to the outline of included bowlders.

[1] *Beiträge zur geol. Karte d. Schweitz*, N.F., XXXVI, 1912.

[2] H. Rosenbusch, *Elemente der Gesteinslehre*, 1901, Figs. 73 and 74; C. K. Leith and W. J. Mead, *Metamorphic Geology*, 1915, Fig. 10.

[3] Paul Niggli, *Beiträge zur geol. Karte d. Schweitz*, N.F., XXXVI 1912; F. H. Lahee, "Crystalloblastic Order," etc., *Jour. Geol.* (1914), 500–515; H. Backlund, *Geol. För. För. Stockholm*, XL (1918), 101–203.

As the matrix is usually made up of alternating lamellae of mica and quartz it is possible that the quartz is dissolved in the direction of stress and deposited perpendicularly to it, while the mica is stable under prevailing conditions. This explanation might apply to some cases where the garnets have the appearance of having grown by forcing the schist apart. Anyway, such an action would involve an increase in volume while certainly the whole tendency in crystalline schists is more toward compression than expansion. The microscopic evidence, therefore, favors the view that replacement in crystalline schists has taken place by equal volumes, though the possibility cannot be denied that under heaviest stress the mode of replacement may be so altered that a smaller volume results.

The occurrence in many of these rocks of abundant crystals of heavy aluminum silicates raises the question whence came this concentration. The alumina could not have been derived only from the replaced host minerals; it must have been concentrated from material some distance away. It seems then that it would be necessary to assume the presence of moving liquid or gaseous solutions. And if moving solutions are admitted there is no essential difference between replacement in this case and in that of static metamorphism. These solutions would have carried other material from the outside, and the difference in volume between the newly formed heavy minerals and the dissolved host minerals would be equalized by new deposits whereby the demand for replacement by equal volume could be satisfied.

It would seem then that the conception of metamorphism under stress here outlined involves somewhat free circulation and limited addition and subtraction of material, with strong tendency toward the preservation of volume.

This is to some degree in opposition to the views of Rosenbusch and Grubenmann but in line with a recent paper by Leith and Mead,[1] in which the convergence to mineral type in dynamic metamorphism is emphasized. Duparc and others have shown us that the conversion of hornblende to uralite is not a simple paramorphism but a metasomatic process. Leith and Mead point out that the

[1] C. K. Leith and W. J. Mead, "Metamorphic Studies," *Jour. Geol.*, XXIII (1915), 600–607.

composition of a schist tends to approach the distinctive chemical characteristics of the dominant platy or columnar mineral, be it muscovite, chlorite, or amphibole. This is clearly the result of a slow metasomatic action, though this view is not definitely expressed by the authors, and if true indicates that gradual exchange of material cannot be excluded for the crystalline schists.

It is well to recognize that recrystallization in rocks under stress remains a subject beset with many difficulties and uncertainties. Fully conscious of this I advance the foregoing suggestions simply as a tentative effort from the viewpoint of a student of metasomatic action.

DESCRIPTIONS OF SOME NEW SPECIES OF DEVONIAN FOSSILS

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University of Minnesota

A study of materials recently collected from the Detroit River series of Michigan and from the Onondaga limestone of Ontario has revealed numerous forms that cannot be identified with known species. Some of these are too fragmentary to be worthy of description, although the genera are easily determined.

The most fruitful source of this material is the Amherstburg beds in the Stony Island Dry Cut. Here great heaps of the rock removed from this part of the river bed are piled high and are rapidly disintegrating under the weathering processes. In 1916 many of the specimens found were thus badly spoiled and each year is continuing the process to ultimate destruction. Grabau and Shimer[1] have described many of these forms, but there still remain a number of fragments that should be found in well enough preserved specimens for description. Attention has been called to some of the more common genera,[2] some of the species of which are described as follows:

Arachnocrinus ignotus n.sp.[3]

PLATE I, FIG. 1

This is a medium to small sized species of Arachnocrinus. The calyx is too poorly preserved for description, or is too deeply imbedded in the matrix to be seen, but doubtless it is small.

Arms more or less uniform in size, uniserial, long, and showing frequent bifurcations. These bifurcations are not uniformly spaced on the different arms and one arm does not branch within

[1] *Mich. Geol. and Biol. Survey*, Pub. 2, Geol. Ser. 1, 1909 (1910), pp. 87–210.

[2] *Bull. Geol. Soc. Am.*, XXVII (1916), 73.

[3] To Dr. Stuart Weller is due the credit for the identification of the genus to which this specimen belongs.

the limits of the preserved specimen. It probably bifurcates farther out from the calyx. The cross-section of the arms is circular and the shape of the arm plates resembles a truncated cone with the base upward. It is not quite clear whether the number of arms is five or six because the branching in one or two cases begins so near the calyx. Dorsal canal extending throughout the arms.

Horizon and locality.—Onondaga limestone, north shore of Lake Erie, three and one-half miles east of Port Dover, Ontario.

Poterioceras canadensis n.sp.

PLATE I, FIGS. 2–5

Shell small, tapering both ways from the base of the chamber of habitation or last air chamber, and extending to a rather blunt point at the apex. Ventral side strongly curved, dorsal side nearly straight but curving slightly upward near the apex. Transverse section subcircular.

Chamber of habitation relatively large, being about two-fifths of the length of the shell, and more or less pear-shaped.

Air chambers regular, increasing slightly in thickness from the apex to the chamber of habitation. Septa smooth, thin, and concavity rather slight. Suture straight and horizontal.

Siphuncle small and marginal on the ventral side.

Aperture subtriangular. Hyponomic sinus well developed.

Surface of shell nearly smooth, marked only by fine lines of growth.

Horizon and locality.—Onondaga limestone. Hamilton's Quarry, Gorrie, Ontario.

Rhipidomella intermedia n.sp.

PLATE II, FIGS. 1 AND 2

Shell subcircular and more or less lenticular in transverse section. Hinge line equal to slightly more than half the width of the shell. Both valves are convex. The pedicle valve with a flattened area along the median line just in front of the middle and extending to the front margin, where it becomes a broad indistinct sinus. Over the corresponding surface of the brachial valve there is a broad convexity.

Cardinal area probably narrow and small. The cardinal process protruding into the pedicle foramen. Teeth large and conspicuous. The specimen found is an internal mold, but it shows that the surface of the shell was covered by numerous radiating striae which were crossed by concentric growth lines.

The interior shows a strongly impressed muscular impression on the pedicle valve. This resembles very closely the similar impression in *R. vanuxemi* but differs from it in the conspicuous divisions characteristic of that species. In the species here described this muscular impression extends slightly more than half the length of the shell and is divided by a prominent median ridge. The brachial valve shows a slight rounded median ridge which extends about a third of the length of the shell and is continued backward into the cardinal process. The muscular impression in this valve is poorly defined. The crural processes are prominent as in *R. vanuxemi*. While this form resembles closely *R. vanuxemi* it is somewhat intermediate between that form and *R. penelope*.

Horizon and locality.—Amherstburg dolomite, Stony Island Dry Cut in Livingston Channel, Detroit River, near Trenton, Michigan.

Schizophoria prima n.sp.

PLATE II, FIG. 3

Shell transversely elliptical or roundly quadrate, moderately convex. Hinge line approximately straight and equal to about half the width of the shell.

Brachial valve unknown. Pedicle valve with rather prominent umbonal region and sloping abruptly to the cardinal area and extremities. In other directions from the umbonal area the valve is more or less flattened (possibly accidentally) but abruptly curved downward at the margins. The front third shows a broad ill-defined sinus which makes but a slight impression on the front margin. Surface marked by fine radiating striae, which are poorly shown on the internal mold. Concentric growth lines are also visible.

The internal impression of the pedicle valve shows a rather small subquadrate muscular scar, which is bordered by a deeply impressed

margin and partially bisected by a prominent rounded ridge impression. This latter was apparently longitudinally striated while the muscular scars themselves were concentrically marked.

Horizon and locality.—Amherstburg dolomite, Stony Island Dry Cut, Livingston Channel, Detroit River, near Trenton, Michigan.

Stropheodonta delicatula n.sp.

PLATE II, FIGS. 4 AND 6

Shell semi-elliptical, somewhat wider than long. Cardinal extremities produced, hinge line usually greater than the greatest width of the shell.

The specimens found are chiefly brachial valves and of those only the external impression, with rarely a rather poor preservation of the shell. Fragments of the pedicle valve show that it was regularly convex and rather gibbous. The beak was small and slightly incurved and extending beyond the area as in *Stropheodonta demissa*. Brachial valve moderately to deeply concave, usually following rather closely the inside curvature of the pedicle valve, leaving scarcely a sixteenth of an inch as the probable thickness of the animal.

Area of pedicle valve arcuate and more or less triangular; area of the brachial valve apparently flat and uniform in width.

Surface of valves marked by strong radiating striae, rather distantly spaced, and between which are numerous fine striae. In the umbonal region the surface is marked by distinct ribs or costae, which seem to persist for half an inch or more from the beak and then are gradually lost. These radiating surface ornamentations are crossed by numerous growth lines which are occasionally aggregated into more conspicuous wrinkles. This species may be compared with *Stropheodonta galatea*.

Horizon and locality.—Amherstburg dolomite, Stony Island Dry Cut, in Livingston Channel, Detroit River, near Trenton, Michigan.

Nucleospira livingstonensis n.sp.

PLATE II, FIG. 6

Shell nearly circular in outline, rather gibbous and rounded oval in transverse section. Width and length nearly equal.

Hinge line about one-third the width of the shell. Cardinal area very narrow and inconspicuous.

Brachial valve not known. Pedicle valve showing a lightly impressed muscle scar and a distinct median septum, which latter is traceable about one-half the length of the shell.

Surface showing distinct growth lines and rather indistinct radiating markings. These latter can hardly represent the surface spines, but suggest them.

Horizon and locality.—Amherstburg dolomite, Stony Island Dry Cut, Livingston Channel, Detroit River, near Trenton, Michigan.

Loxanena inculta n.sp.

PLATE II, FIGS. 7 AND 8

Shell tapering gradually to a high spire; apical angle 35°. Six or more volutions which are moderately convex or somewhat flattened on the outer surface but rather abruptly curving on the lower side of the whorl. Aperture subelliptical. Surface marked by strong regularly elevated striae, which turn gently backward from the suture and then forward, completing the curve before the periphery of the whorl is reached and below which they have been preserved.

Horizon and locality.—Amherstburg dolomite, Stony Island Dry Cut, Livingston Channel, Detroit River, near Trenton, Michigan.

Callonema perlata n.sp.

PLATE III, FIGS. 1 AND 2

Shell depressed turbinate; spire low, consisting of five or more volutions which increase in size gradually and are oval in cross-section. Apical angle 138°. Umbilicus large and shallow. Suture moderately depressed and marking the outer margin of the preceding whorl.

Surface marked by medium to coarse striae of growth, which pass obliquely outward from the suture, continue over the periphery, from which they curve gently backward, and then disappear in the umbilicus. The coarseness of the striae increases with distance from the apex of the spire.

Horizon and locality.—Amherstburg dolomite, Stony Island Dry Cut, Livingston Channel, Detroit River, near Trenton, Michigan.

DESCRIPTION OF PLATES

All figures are natural size.
Mr. G. S. Barkentin, delineator.

PLATE I

Fig. 1. Arachnocrinus *ignotus* n.sp.
1. Dorsal (?) view.

Figs. 2–5. *Poterioceras canadensis* n.sp.
2. Ventral view.
3. Dorsal view.
4. Lateral view.
5. Posterior view of the last chamber preserved and showing position of siphuncle.

PLATE II

Figs. 1–2. *Rhipidomella intermedia* n.sp.
1. Brachial valve.
2. Pedicle valve of same specimen.

Fig. 3. *Schizophoria prima* n.sp.
3. Pedicle valve.

Figs. 4–5. *Stropheodonta delicatula* n.sp.
4. Impression of brachial valve showing impression of part of cardinal area of pedicle valve.
5. Impression of brachial valve of another specimen.

Fig. 6. *Nucleospira livingstonensis* n.sp.
6. Pedicle valve.

Figs. 7–8. *Loxonema inculta* n.sp.
7. A small specimen showing surface markings fairly well preserved.
8. A large specimen showing surface poorly.

PLATE III

Figs. 1–2. *Callonema perlata* n.sp.
1. Lateral view showing character of surface markings.
2. Apical view.

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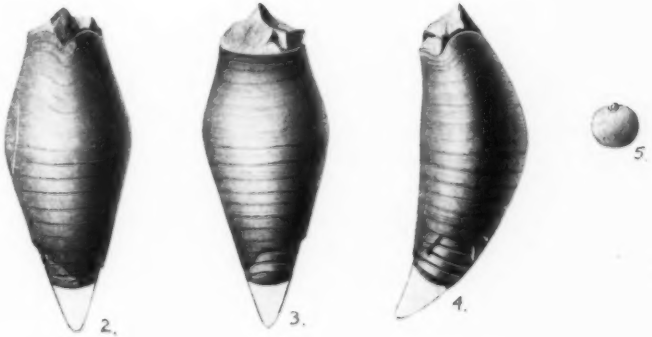

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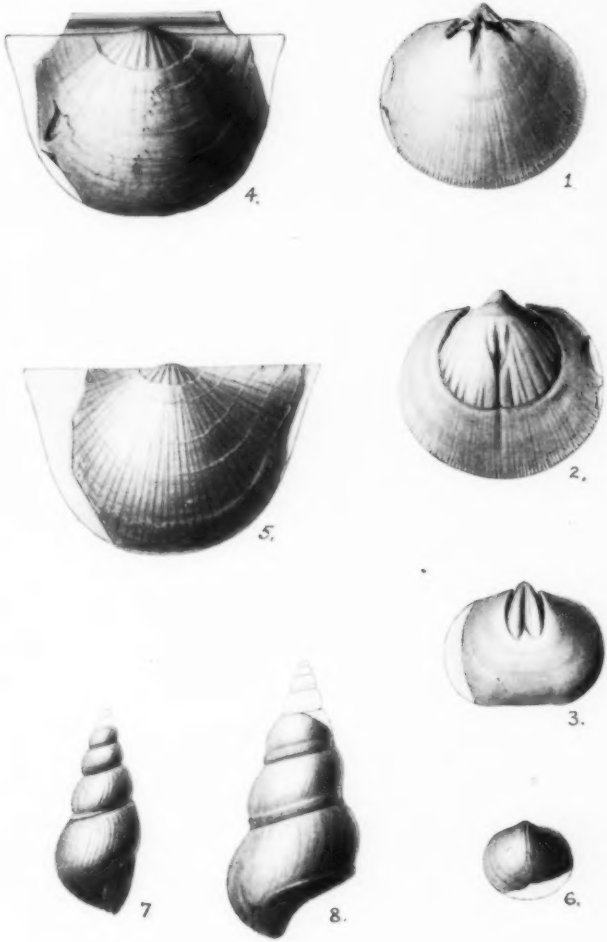
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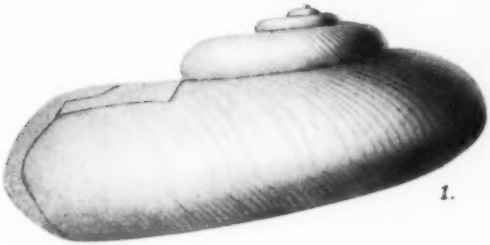

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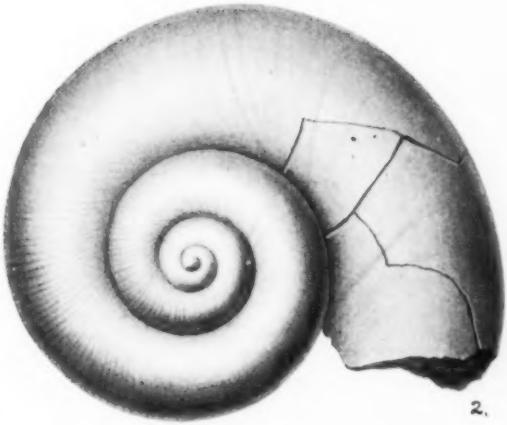

2.

ON THE NATURE AND ORIGIN OF THE STYLOLITIC STRUCTURE IN TENNESSEE MARBLE[1]

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INTRODUCTION
CHARACTER OF THE PHENOMENA
Early Observations, and Names Applied to It
Description of the Structure in Tennessee Marble
THEORIES OF ORIGIN
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Pressure Theory
Gas Theory
Erosion Theory
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SUMMARY

INTRODUCTION

The stone known commercially as "Tennessee marble" constitutes what the government geologists have called the Holston formation, which is of Ordovician age. The quarries are located chiefly in the central portion of the East Tennessee Valley with Knoxville as a center. The marble is sub-crystalline to crystalline in texture and varies in color from light pink and gray to differing shades of red, dark chocolate, and cedar. At present the light pink and gray are the varieties most in demand. The formation is from 200 to 400 feet thick, though by no means is all of this suitable for decorative purposes. As a result of folding, accompanied in places by faulting, the outcrops occur in belts extending from northeast to southwest. The strata dip usually 25 to 35

[1] Read before the Tennessee Academy of Science, November 26, 1915, and the American Association for the Advancement of Science, Pittsburgh, December, 1917. (Abstract, *Science*, New Series, XLVII [1918], 492.)

degrees to the southeast, but in places they are inclined in the opposite direction. The marble takes a fine polish and is much favored by architects for interior decoration. It is widely used for both interior and exterior work and may be seen in many buildings throughout the United States and even in foreign countries.

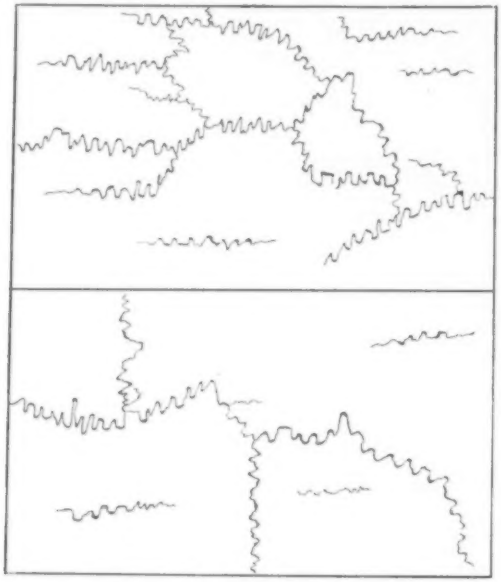

FIG. 1.—Examples of Stylolites in Tennessee Marble

One of the striking features of the marble is the presence of dark-colored, interlocking seams or sutures known technically as "stylolites." This structure, which is prominently displayed on the polished surfaces of slabs cut across the bedding planes of the stone, is known among the quarrymen as "crowfoot" and "toe-nails," and various theories have been proposed to account for it. It first attracted attention in the Muschelkalk of Europe but has been observed to occur in limestones generally, though some of the best examples appear in the Muschelkalk of Europe, the Clinton

limestone of New York, the Bedford limestone of Indiana, and the Tennessee marble.

CHARACTER OF THE PHENOMENA

Early observations, and names applied to it.—According to Rothpletz this structure was first mentioned by Mylius in 1751. In 1807 Friesleben described it as "apfenförmiger Strictur der Flözkalkstein," and later Hausman referred to it as "Stängelkalk." The name "lignilites" was applied to these structures by Eaton in 1824. In 1838 they were called "epsomites" by Vanuxem, who likened them to the sutures of the human cranium, while Hunt gave them the name "crystallites" in 1863. The name "stylolites," from *stulos*, "a column," was given them by Kloden in 1828.

Description of the structure in Tennessee marble.—The sutures present in Tennessee marble have the typical appearance of "stylolites" as described by authors. They consist of slickensided columns of stone projecting alternately from the surfaces on either side of a parting or fracture plane whereby the two parts of the stone become intimately interlocked. As a rule the union is so intricate and firm that the stone will break more readily elsewhere than along the suture. The columns vary in length from a small fraction of an inch to four inches or more, and in diameter they may be two inches or more, though usually they are much under this. The sides of the columns are fluted and striated in the manner characteristic of "slickensides." Occasionally the columns are broad and relatively short with tops studded with the small projections. The columns are usually capped with a thin layer of clay. In places the clay is more abundant and in such cases may weather out in the cliff, leaving cavities. The occurrence of a shell or other fossil capping the column is frequently mentioned by authors but such instances are rare in the Tennessee marble.

In general the sutures are approximately parallel with the planes of bedding, but frequently they may be observed cutting the planes of sedimentation obliquely or even at right angles. In places they appear as a network intersecting the stone in all directions. In some portions of the rock the horizontal sutures are numerous and closely spaced while in others they are several feet apart. In the

majority of cases they thin out without a trace of parting beyond, but not infrequently they are terminated abruptly by a cross-fracture or suture. Branching of the horizontal sutures is common and often the two branches meet again, thus inclosing lens-shaped masses of stone.

On surfaces showing both horizontal and oblique sutures it is observed that the columns are all at right angles to a common plane which is approximately the plane of sedimentation. In their descriptions of stylolites, Marsh, Grabau, and others state that the columns project at right angles from the opposing faces, but this is true, according to our observations, only of those sutures that follow the planes of sedimentation. Where the suture is oblique to this plane the columns are inclined, the inclination being greatest in those sutures which are most oblique to the plane of sedimentation. Where the suture is at right angles to the plane of sedimentation, distinct columns are wanting, the suture appearing as a wavy or zigzag line apparently representing the variety of stylolitic structure termed "pressure-suture" by some authors.

THEORIES OF ORIGIN

Only brief mention will be made here of the earlier suggestions offered in explanation of this structure. Those desiring a fuller treatment are referred to Wagner's exhaustive paper,[1] which includes a fairly complete bibliography of the subject.

Organism theory.—Eaton,[2] who appears to have been the first to offer an explanation of these structures, considered them to be of organic origin and named them "lignilites" in the belief that they were the columns of corals. Four years later, Kloden[3] described them as a distinct species of organism under the name *Stylolites sulcatus*. These, however, had few followers, though Kloden's name "stylolites" has been retained for the structure.

Crystallization theory.—Bonnycastle in 1831 considered the structure as a mineral formed by infiltration. The mineral expla-

[1] Georg Wagner, *Geologische und paleontologische Abhandlungen* (Koken), N.F. (1913), Band XI (XV), Heft 2, pp. 101–27, Plates X, XI, XII.

[2] Amos Eaton, *Geology of New York*, 1824.

[3] F. Kloden, *Die Versteineringen der Mark Brandenburg* (1828), 1834.

nation was accepted in 1838 by Vanuxem and the name "epsomites" applied to the structure in the belief that it represented the crystallization of sulphate of magnesia. Among others who accepted the mineral theory with modifications were James Hall, Ebenezer Emmons, and T. Sterry Hunt, the last named proposing for them the name "crystallites."

Pressure theory.—The first to suggest that this structure is due to differential compression of sediments before consolidation was Quenstedt,[1] followed soon after by Marsh.[2] Experimental demonstration of the theory was attempted by Gumbel,[3] but as Wagner points out the results were not convincing.

Following Marsh's explanation it is assumed that a thick bed of carbonate of lime is deposited as a fine soft ooze over the surface of which are scattered the remains of organisms, such as shells, etc. This is then covered by a very thin layer of argillaceous mud, upon which is deposited more calcareous material, whose increasing weight tends to condense the mass below. As a result of the resistance offered by the shell or other organic substance "the surrounding material will be carried down more rapidly, thus leaving columns projecting above, each protected by its covering and taking its exact shape from its outline." According to this theory, therefore, the structure is due to differences in the amount of compression in the material beneath and around the shell before consolidation as a result of the weight of the overlying mass. The fact that the columns are not always capped by shells (in Tennessee marble rarely), and, further, as pointed out by Grabau,[4] that there is no evidence of deformation, or crowding or squeezing around or above the columns, is against the theory of simple compression either before or after consolidation. Moreover, the fact that the sutures are often oblique or even at right angles to the plane of sedimentation is clearly opposed to this theory. The occurrence of such

[1] A. Quenstedt, *Epochen der Natur*, 1861, pp. 200, 489.

[2] O. C. Marsh, *Proceedings of the American Association for the Advancement of Science*, XVI (1867), 135–43.

[3] Gumbel, *Zeitschr. Deutsch. geol. Ges.*, 1882, p. 642; *ibid.*, 1888, p. 187.

[4] A. W. Grabau, *Principles of Stratigraphy*, 1913, p. 787.

transverse sutures was observed by Marsh, but he seems to have failed to recognize their negative bearing on the pressure theory.

Gas theory.—Zelger,[1] in 1879, after detailed work on the stylolites considers them due to the escape of gases through the soft plastic mass and the later filling in of the passageways.

Erosion theory.—In his description of this structure as it occurs in the Bedford limestone of Indiana, Hopkins[2] reviews the theories given therefor and suggests that some may be due to the formation of cracks in the drying of limestone mud while others look like a rain- or spray-washed surface, though he adds that "possibly the escape of gases, as advocated by Zelger, may have acted in some places."

Solution theory.—The theory that the stylolitic structure is due to unequal solution along suture or fracture planes in calcareous rocks after consolidation was first proposed by Fuchs,[3] later accepted by Reis,[4] and more fully established by Wagner.[5] Quoting from Grabau,[6]

> if solution takes place on the concave surfaces of both the upper and lower faces of the fracture, the result must be the production of a series of tooth-like projections from both sides of the fissure, which, owing to the pressure of the overlying rock, interpenetrate more and more as room is made by solution. In other words the rock opposite the end of each tooth-like projection is dissolved away—the hollows are deepened and the teeth, gliding under pressure, penetrate deeper and deeper into the opposite bed while at the same time they become longer by the deepening of the hollows which surround and isolate them. The residual clay left on solution comes to rest as a cap on the top of the stylolite protecting this top from solution.

The striations on the sides of the stylolite are the result of abrasion between the opposing surfaces in the process of compression. As the sides of the columns are largely free from pressure there is little or no solution there. The presence of a shell or other fossil favors the process, as it is less readily soluble than the inclosing rock.

[1] Zelger, *Neues Jahrb. für Mineralogie*, 1870, p. 833.

[2] T. C. Hopkins, *Twenty-first Annual Report of the Indiana Geological and Natural History Survey*, 1896, pp. 305–8.

[3] T. Fuchs, *Ber. d. K. Akad. d. Wiss. Math. nat. Kl. Wien*, 1894.

[4] O. M. Reis, *Geognost. Jaresh. d. K. Bayr. Obergamtes München*, Band 14, 1901; also Band 15, 1902.

[5] Georg Wagner, *op. cit.* [6] A. W. Grabau, *op. cit.*

It is held by some that the sutures seen in Tennessee marble represent original stratification planes or partings which are occupied by very thin laminae of silt, and beneath this silt unequal solution has taken place as indicated above. That the opposing faces along clay partings in limestones are affected by unequal solution is a matter of common observation. Often the opposing surfaces of the beds will be seen to have rounded elevations and depressions which alternate with each other, but there is no interlocking as in the case of true stylolites. If the clay parting is very thin, however, it is quite likely that a true stylolitic structure may develop along such planes, and that some of the sutures in Tennessee marble are of this character is probable. But from the study of hundreds of examples of the sutures in the Tennessee marble, the writer is convinced that in the main they represent fracture planes. Convincing proof of this appears in their irregularity and frequent tendency to cut across the sedimentation planes obliquely or even at right angles. Wagner, who described them as occurring along fractures, stressed this point when he says that, whereas under the pressure theory the sutures must follow the plane of sedimentation, in the solution theory they may intersect the stone in any direction.

Inasmuch as the columns manifest a general tendency to assume a position at right angles to the plane of sedimentation and since it is probable that static as opposed to dynamic pressure has been most effective in furthering solution this would seem to offer evidence that the stylolitic structure was more or less advanced if not completed before the rocks assumed their present tilted position as a result of folding and faulting at the close of the Paleozoic era.

Grabau considers that the length of the column is a fair measure of the amount of material removed from both sides of the fracture.

SUMMARY

Polished slabs of Tennessee marble are usually marked by irregular zigzag lines likened by Vanuxem to the sutures of the human skull and now known generally as "stylolites," the origin of which is a subject of frequent inquiry. These structures consist of striated

toothlike projections or columns projecting from the opposing surfaces along a plane of fracture whereby the two parts of the stone are so intimately interlocked that often the slab will break more readily elsewhere than along the suture.

The theory that they are due to differential compression in beds of soft calcareous sediments separated by a thin film of clay was first proposed by Quensted (1861) and adopted by Marsh (1867), Gumbel (1882), Rothpletz (1900), and others. The absence of evidences of compression and squeezing as also the fact that the sutures are often more or less oblique to the planes of sedimentation or may form a network of intersecting lines are adverse to this theory.

The most satisfactory explanation of these remarkable structures is the solution theory first proposed by Fuchs (1894) and ably supported by Reis (1901, 1902) and Wagner (1913). According to this theory the structures are due to unequal solution along planes of fracture, or extremely thin partings after the consolidation of the rock. As the result of compression due to the weight of the overlying mass, solution will take place more rapidly on the concave surfaces opposite the columns, thus causing these to penetrate deeper and deeper into opposing surface. The residual clay comes to rest as a cap on the top of the column, thus protecting it from solution. Fossil shells sometimes found on top of the column favor the process, as they are less readily soluble than the inclosing rock.

THE VALLEY CITY GRABEN, UTAH[1]

C. L. DAKE
Rolla, Missouri

During the course of reconnaissance work undertaken in 1917 over much of southern Utah, the writer observed an interesting structure which seems worthy of a brief description. It is located in Townships 22 and 23 South, Ranges 19 and 20 East, in Grand County, and is plainly visible along the road between Thompsons and Moab, near Valley City.

STRATIGRAPHY

The stratigraphy of the general region is simple, and is well described in reports by Lupton[2] and Woodruff,[3] to which the reader is referred for greater detail. The oldest formation exposed in the immediate vicinity is the Dolores, consisting of about 1,300 feet of variegated sandy shales and soft sandstones of Triassic age. Red, pink, and gray are the dominating colors. The formation is relatively nonresistant, and usually comprises plains and broad valleys. Above the Dolores occurs the La Plata sandstone, probably Jurassic in age. This is the most prominent formation in the district, and consists of two tan-colored, massive, highly cross-bedded sandstones separated by about 100 feet of red sandy shale. The sandstones are prominent cliff-makers and form the pronounced fault-line scarp near Court House Spring on the Thompsons-Moab road. Occasional lenses of unfossiliferous limestone a few feet thick and a few yards in extent were noted in the sandstone in places. Above the La Plata sandstone occurs the McElmo formation, of Jurassic age, consisting of about 1,000 to 1,200 feet

[1] Published by permission of Valerius, McNutt, and Hughes, Consulting Petroleum Geologists, Tulsa, Oklahoma.

[2] C. T. Lupton, "Oil and Gas near Green River, Grand County, Utah," *U.S. Geol. Survey, Bull. 541* (1914), p. 115.

[3] E. G. Woodruff, "Geology of the San Juan Oil Field, Utah," *U.S. Geol. Survey, Bull. 471* (1912), p. 76.

of shales and sandstones. No fossils were noted in this vicinity, but near Teasdale, in Wayne County, the writer found abundant marine fossils, chiefly pentagonal crinoid stems in a thin limestone, a few feet above the contact of this formation with the underlying massive sandstones. Fossils were also found at the same horizon near Loa. The McElmo beds are highly variegated, red, pink, gray, green, and maroon being common shades. Gypsum, in beds up to 100 feet or more thick, occurs in the lower half of the formation. About 400 feet below the top of the McElmo occurs the Salt Wash member, a very conglomeratic gray coarse sandstone. The McElmo has a highly characteristic bad-land topography. Following the McElmo occurs the Dakota formation of Cretaceous age, usually 25 or 30 feet thick, a coarse gray sandstone, at places highly conglomeratic and outcropping in hogbacks. Above the Dakota is the Mancos, a bluish-gray soft shale 2,000 to 3,000 feet thick, forming broad plains.

STRUCTURE

Lupton,[1] on his map of the Green River field, does not show the formations in the area involved in this description, but he writes the word "anticline" along the axis of the structure in question, leaving the area blank, since it was outside the field involved in his report. As seen from the west, along the Green River-Moab road or the Thompsons-Moab road (Fig. 1), the structure appears to be a simple anticline, the limbs of which rise gradually from the adjacent plain of Mancos shale to the northeast and southwest. Two scarps about a mile apart face each other from these limbs and overlook a central or axial valley which strikes about N. 45° W. At first this was supposed to be a simple anticlinal valley, but the extreme straightness of these scarps for several miles aroused suspicion, so a careful examination of the structure was made. It was found to be a well-developed anticline, along the crest of which occurs a typical graben or down-faulted trough about a mile wide (Fig. 2.). The relationships are clearly brought out in Figs. 3 and 4. Outcrops of Mancos shale were found almost in contact with La Plata sandstone. This would give the fault a displacement of perhaps 1,200 feet or

[1] *Loc. cit.*

FIG. 1.—The Valley City anticline, seen from about three miles west of Valley City, Grand County, Utah.

FIG. 2.—Within the graben of the Valley City anticline, Grand County, Utah. The walls on either side are fault-line scarps.

more. No fossils were found in the Mancos, but it is so highly characteristic in color and texture as to afford little doubt of its proper identification. Still farther southwest the graben seems to be floored with McElmo beds, probably the Salt Wash member,

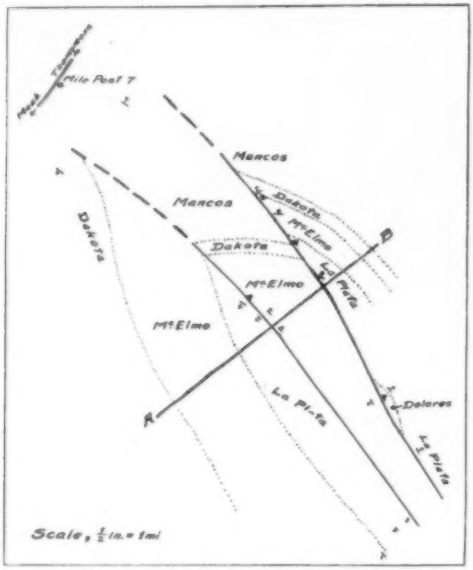

FIG. 3.—Map of portion of Valley City graben, Utah

FIG. 4.—Section across Valley City graben, Utah

consisting of coarse gray conglomeratic sandstone. While it is possible that these beds are Dakota conglomerate, from their general character it seems much more probable that they are Salt Wash. They lie at the base of a well-pronounced fault-line scarp of La Plata sandstone several hundred feet high, along the base of which the Dolores is probably exposed. If so, this would involve about 2,000 feet of displacement.

Along the bottom of the graben plain, toward the base of the scarps on both sides, the beds show high local dips that are presumably the result of drag along the fault planes.

While the identification of the beds in the graben plain was wholly on lithologic grounds and was rendered somewhat difficult by scarcity of outcrop, there seems to be little doubt that the foregoing interpretation is the proper one. And while grabens are by no means rare, a graben occupying the axial line of a well-defined anticline seems sufficiently unusual to merit some attention. The area is probably complicated by cross-faulting. Since only one day was spent studying the structure, it is more than probable that important features escaped detection. The entire region is one that offers possibilities of interesting structural and stratigraphic work.

The topographic expression of this structure is clearly shown on the old United States Geological Survey La Sal Reconnaissance sheet, east of the road leading from the railroad to Moab. The two inward-facing scarps with the central valley and the outward dip slopes are plainly marked.

While no detailed work was done at Moab, the writer has seen some evidence to lead to the conclusion that the Moab plain, extending southeast from the village of Moab, is possibly also a similar graben.

Reviews

Chemical Analyses of Igneous Rocks. Published from 1884 to 1913 Inclusive. By Henry Stephens Washington. U. S. Geol. Survey, Prof. Paper 99. Washington: 1917.

Students of petrology are still further indebted to Dr. Washington for a great store of chemical data in the form of 8,602 rock analyses, gathered together from all manner of geological and petrographical publications and from personal contributions of analyses which were awaiting publication. The value of such a carefully prepared and vast accumulation of rock analyses is obvious to all who desire to know the chemical composition of igneous rocks and wish to compare the rocks of different regions. The labor involved in collecting and arranging the analyses and in calculating the mineral norms is indicated by the statement of the author that "on an average the 4,980 analyses in Part I took 45 minutes apiece and those in Parts II, III, and IV (3,622) took about 30 minutes or more apiece," in all more than 5,546 working hours.

The analyses have been arranged according to their quality in four groups: (I) superior analyses of fresh rocks, designated as "excellent," "good," and "fair," except those which could not be classified properly in the quantitative system of rock classification; (II) superior analyses, generally good or fair, not properly classifiable in the quantitative system; (III) superior analyses of tuffs and of weathered or altered rocks; (IV) analyses deemed poor or bad. Nearly 5,000 analyses have been classified and arranged according to the quantitative system of classification of igneous rocks, and form the major portion of the collection, which includes those in the first collection by Dr. Washington, published as *Professional Paper 14*, in 1903. The new publication is a revision and expansion of the former, in which Part I contained 1,711 superior analyses. The amount of expansion is shown by a comparison of the number of analyses published in each paper. In No. 14 the total was 2,881, of which 1,711, or 59 per cent, were placed in Part I. In No. 99 the total is 8,602, of which 4,980, or 58 per cent, are put in Part I. There are 5,721 more in the new collection, or nearly three times as many as in the former one. This shows an increased production in

thirteen years of double that of the previous sixteen years and a betterment of the quality, since nearly 1,500 superior analyses are placed in Parts II and III of the new collection; that is, 6,471 superior analyses were made in the thirteen years since 1900.

The text contains a critical discussion of the character and use of analyses: their representativeness, accuracy, and completeness. The method by which the author rated the analyses is explained. It is this rating, which was employed in the earlier publication, that has had much to do with the marked improvement in more recent analytical work. An inspection of the geographical distribution of the localities from which rocks have been analyzed shows some extensive gaps, even in regions accessible to petrographers, as the author points out. There is an important commentary on names that have been applied by various petrographers to divisions of the Quantitative System of Classification, as well as a concise statement of the Quantitative System, and of the method of calculating norms from chemical analyses, besides numerical tables for use in the calculation. It would be a great help to petrographers if this portion of the book were printed and published separately.[1] The thorough indexing of the book according to four systems adds greatly to its usefulness.

J. P. IDDINGS

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